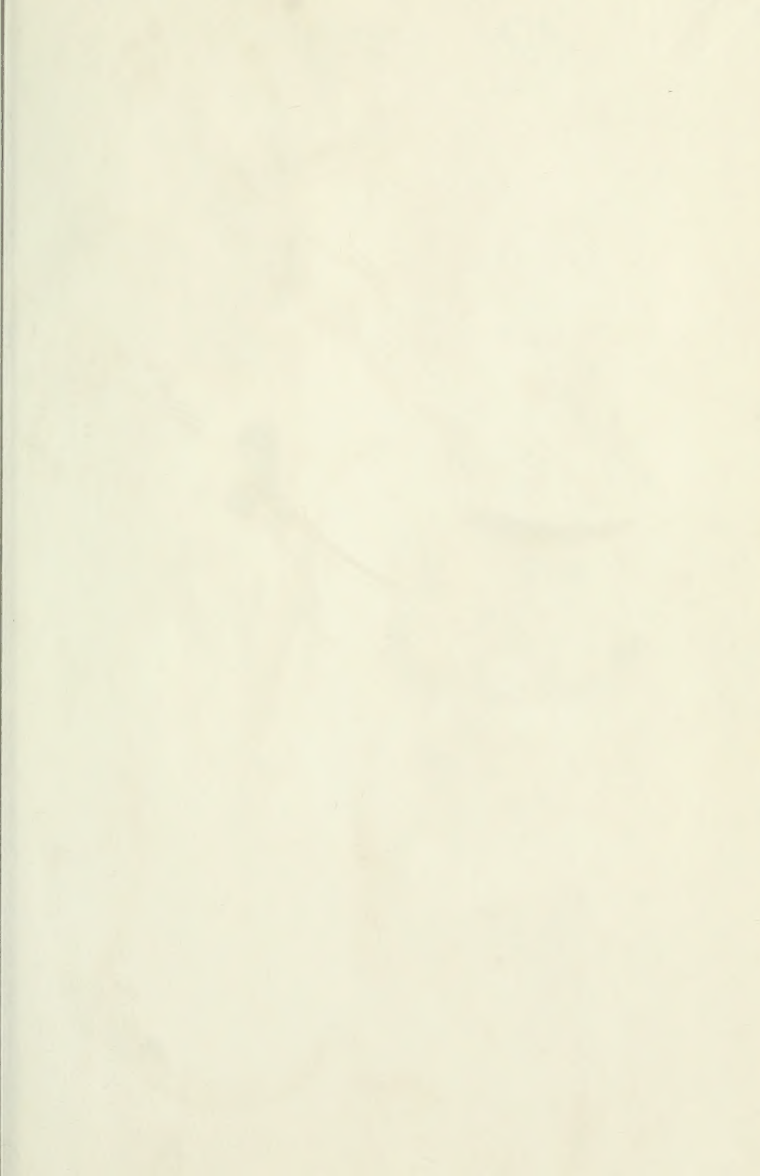
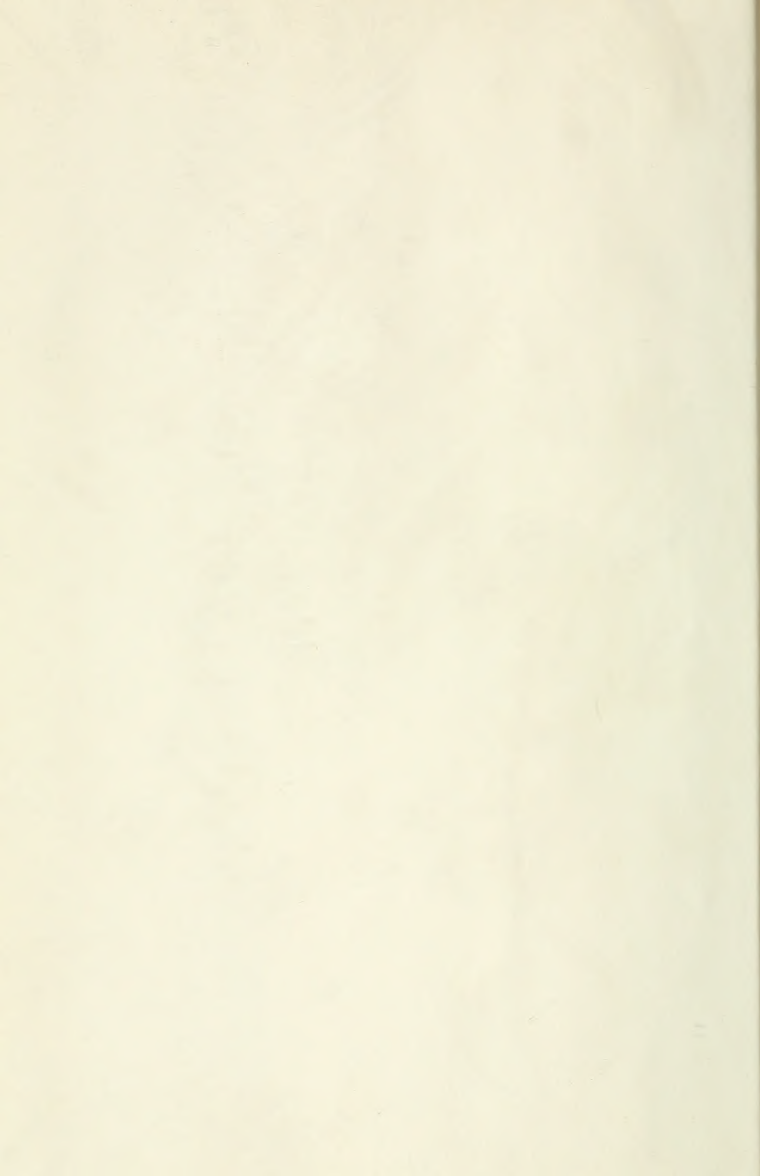


3 1761 04186 1402





374B

77

COLOUR AND METHODS
OF COLOUR REPRODUCTION

ptics
M

COLOUR AND METHODS OF COLOUR REPRODUCTION

BY

L. C. MARTIN

D.I.C., A.R.C.S., D.Sc.

Lecturer in the Optical Engineering Department,
Imperial College of Science and Technology, South Kensington

WITH CHAPTERS ON
COLOUR PRINTING AND
COLOUR PHOTOGRAPHY

BY

WILLIAM GAMBLE

F.R.P.S., F.O.S.

Editor of the "Process Year Book"

181591
27.6.23

BLACKIE AND SON LIMITED

50 OLD BAILEY LONDON
GLASGOW AND BOMBAY

1923

DEDICATED
TO
LADY ABNEY

IN MEMORY OF A GREAT WORKER
IN THE SCIENCE OF COLOUR:
SIR WILLIAM DE W. ABNEY
K.C.B., F.R.S.

PREFACE

Part I of the present book aims at giving a simple account (which in the main should be intelligible to the non-specialist reader) of the chief facts of the theory of colour measurement and nomenclature, and also seeks to indicate how the theory may help out practice in various directions. It is also definitely introductory to the second part. Part II is intended to provide an introduction to the more advanced study of colour measurement and colour vision; some knowledge of physics on the part of the reader is assumed. Part III, which deals with colour printing and colour photography, comes from the pen of Mr. Wm. Gamble, editor of *The Process Year Book*. His wide experience in these technical matters renders his collaboration of great value. It is therefore hoped that the book may be of use to those dealing with colour in the worlds of commerce and art, and also that it may stimulate the interest of others with a scientific training and tempt them to wander into this most fascinating field of inquiry.

A study of the subject of colour vision seems to show that the day of fervid partisanship as between different theories is closing, and increasing knowledge only reveals the long road along which we must travel for a complete explanation of this and other sensory mechanisms. The primary contribution of the pure physicist is now very largely completed in the studies which have grouped around the trichromatic theory, and the results obtained will always be of permanent value from the practical standpoint. To neglect this work because the theory is inadequate to account for all the observed

results may be like neglecting the theory of the steam-engine because it cannot entirely account for the presence of a crowd of people getting out of a train. In this connection a tribute may be paid to the work of the late Sir William Abney, which America at least has appreciated at its true worth. It was a misfortune, indeed, which robbed this subject of Abney and the late Prof. Watson almost at the beginning of a collaboration which promised to be of great value. Abney's apparatus remains in the Department of Applied Optics at the Imperial College through the generosity of Lady Abney; but, owing to the financial difficulties of the present time, it is being used for teaching only, and no longer for the important researches for which laboratory and apparatus are so singularly adapted. It is now more than ever necessary that the limitations of the trichromatic theory shall be explored, still by physically sound methods, but by men who are fitted to understand the psychological and physiological view-points. Furthermore, there is a great deal of work which needs the most careful verification and checking.

For the reason of the limitation of the scope of the present work, I have refrained from a discussion of the theories, electrical and otherwise, which seek to explain the primary translation of the energy of electro-magnetic radiations into the nervous and mental phenomena which we experience as light and colour. Any treatment of these theories within the present limits would be inadequate and unsatisfactory, and the effect of their incidence on the older and more fundamental theories seems still uncertain.

In conclusion it may be hoped that this book may do something at least to enhance the enjoyment of colour by those who read it. Philosophy is less "proud" than she was, and there is room in the world for men like Sir William Abney and the late Prof. Silvanus P. Thompson, philosophers first, but something of artists too.

In reading for the purposes of the present book I have been especially helped by Abney's *Researches in Colour Vision*, Parsons' *Introduction to the Study of Colour Vision*, Luckiesh's *Color*, and not least by the valuable articles in the *American Journal of Physiological*

Optics, a new review published by the research division of the American Optical Company, and edited by Dr. Charles Sheard.

My best thanks are due to Dr. R. S. Clay, Mr. W. Gamble, and Prof. F. J. Cheshire, C.B.E. (who have read the proofs or MS. of Parts I and II) for their interest and helpful suggestions. I am also indebted to many firms¹ for information and catalogues. Permission to use illustrations has been kindly given by Messrs. Eimer & Amend, Adam Hilger, Ltd., and The Munsell Color Company. Mr. B. K. Johnson, of this college, has drawn many of the diagrams.

¹ Messrs. Richardson & Co., Ltd., G. Rowney & Co., Ltd., Shackell, Edwards, & Co., Ltd., Tintometer, Ltd., and Winsor & Newton, Ltd.

L. C. MARTIN.

Optical Engineering Department, Imperial College of
Science and Technology, South Kensington.

July, 1922.

CONTENTS

PART I

CHAPTER

PAGE

I. THE NATURE OF LIGHT AND COLOUR.

Light and Colour, Introductory—Ray Paths in Prisms and Lenses—The Eye—Newton's Experiment—Selective Reflection and Absorption—Fluorescence—Ultra-violet and Infra-red Regions of the Spectrum—Colours in Nature—Hue and Wavelength—Definitions - - - - - 1

II. COLOUR ANALYSIS AND SYNTHESIS.

The Spectroscope—Direct-vision Spectroscopes—Selection of Particular Wave-lengths—Additive Mixing of Coloured Lights—Experimental Methods and Results—Mixing of Monochromatic Lights—Trichromatic Theory—Complementary Hues—Colour Discs—Colour Mixture by "Over-lapping"—Chromoscopes - 14

III. THE COLOURS OF MATERIAL OBJECTS: THEIR NOMENCLATURE AND MEASUREMENT.

The Colours of Objects—Colour Filters—Dichroism—Spectral Reflection of "Coloured" Materials—Subtractive Colour Mixing and Mixing of Pigments—Colour Nomenclature and Measurement—Requirements of an Ideal Colour Notation—Requirements for an Ideal Colour Nomenclature—Colour Charts—Maxwell's Colour Triangle—Colour Pyramids—Titchener's Colour Pyramid—Munsell's Colour System—Nobili's Colour Scale—Practical Methods of Colour Measurement—General Ideas of the Purpose of the Colour-patch Apparatus—Spectrophotometers—Colorimeters - - - - - 23

IV. COLOUR IN REGARD TO ILLUMINATION.

Natural and Artificial Light—Radiating Bodies—Lummer and Kurlbaum's Experiments—Spectral Distribution of the Energy of Light Sources—Daylight and its Variation—Characteristics of Artificial Lights—Effects of Variations in Light on the Colour of Objects—Artificial Modifications in the Colour of Light—Artificial Daylight—Possible Efficiency—Correction by Filters and Reflectors—Coloured Light for "Magical" Stage Effects - - 39

V. COLOUR IN HUMAN EXPERIENCE.

The Development of the Use and Study of Colour—Colour Preferences—Colour Harmony—Colour Music—Protective Colouring and “Camouflage”—Colour and Health—Visual Fatigue—Colour Fatigue—Sundry Visual Effects—Simultaneous Contrast—Effects of Intensity—Purkinje Effect - - - - -

53

VI. COLOURING MATERIALS.

Colouring Materials—Pigments and Painting—Precautions in Mixing Pigments—Stability of Pigments—Action of Pigments on Reflected Light—Colouring Materials for Glass, Pottery, and Enamels—Glasses for Eye Protection—The Dyes—Addendum to Chapter VI—Chemical Classification of Pigments and Tables of Stability - - - - -

63

PART II

VII. THE EYE AND ITS REACTIONS TO LIGHT; PHOTOMETRY.

Construction of the Eye—Colour Fields—Non-achromatism of the Eye—Visual Measurement and Comparison of Brightness—“Inverse Square” Law—Rotating Sector—Changes of Aperture—Photometric Wedges—Polarizing Prisms—Reactions of the Eye to Light—Hue “Limen”—Tone Limen—Contrast Sensibility—Purkinje Effect—“True” Sensation Measurement—Effect of Dispersion on the Distribution of Energy in the Spectrum—Variation of Luminosity in the Spectrum—“Flicker” Photometer Methods—Threshold of Vision for Different Coloured Lights - - - - -

77

VIII. INSTRUMENTS FOR COLOUR MEASUREMENT.

Colour-patch Apparatus—Diffraction Gratings—Spectrophotometers—König-Martens Photometer and Spectrophotometer—Integrating Cylinder—Photometric Comparison Cube—Nutting's Colorimeter—Colorimeters depending on Three-colour Mixture—Ives Colorimeter—Bawtree Colorimeter—Colorimeters depending on Subtractive Mixture—The Tintometer—Jones's Colorimeter—Arons' Colorimeter—Duboscq Colorimeter—Nephelometer—Accuracy of Colour Measurements - - - - -

96

IX. COLOUR VISION.

Introductory—Statement of Theories: (1) Trichromatic, (2) Hering's, (3) Ladd-Franklin, (4) Edridge-Green—Measurement of the Hue Sensations in the Spectrum—Primary Hue Sensations—Determination of Hue, Saturation, and Brilliance from Spectrophotometer Readings—Change in Hue of Spectrum Colours—Visual Fatigue—Colour Fatigue—Allen's Investigations - - -

117

Introductory—Types of Colour Blindness—The Colour-blind Standpoint—Colour Blindness on the Trichromatic Theory—Necessity for Tests of Colour Vision—Actual Tests: (1) The Lantern Test, (2) the Bead Test, (3) Holmgren Wool Test, (4) Card Tests, (5) Colour-patch Test, (6) Measurement of Sensation Deficiency, (7) Luminosity Test, (8) Anomalous Matches - 130

XI. COLOUR PRINTING -	-	-	-	-	-	-	151
XII. PHOTOGRAPHY IN COLOURS -	-	-	-	-	-	-	160

1.	Transmission and Reflection of Light	-	-	-	-	-	-	-	173
2.	Units of Light	-	-	-	-	-	-	-	177
3.	Dichroism	-	-	-	-	-	-	-	178
4.	Table showing Wave-lengths of Spectrum Lines	-	-	-	-	-	-	-	179
5.	Table showing Typical Registration of Colour	-	-	-	-	-	-	-	180
6.	Table showing Temperatures of Sources of Light	-	-	-	-	-	-	-	180
7.	Table showing Spectral Luminosities and Percentage Composition of Spectral Lights	-	-	-	-	-	-	-	181
8.	Note on Fig. 30	-	-	-	-	-	-	-	182
	INDEX	-	-	-	-	-	-	-	183

COLOUR METHODS

PART I

CHAPTER I

The Nature of Light and Colour

In dealing with light and colour sensations we must never forget that these are really the interpretation, given by the brain, of certain physical phenomena. Thus, for example, pressure on the eyeball produces the sensation of light even in complete darkness, and it is a simple matter to produce colour sensations independently of the presence of correspondingly coloured objects or light, as was shown by Fechner in 1838. Benham's disc (fig. 1), when rapidly rotated, shows vivid hues, which are in some way due to different rates of appearing and fading of hue sensations.¹ The disc is merely "black and white", and the experiment thus shows very clearly that "colour" is a subjective phenomenon, which may or may not relate to exterior qualities of light.



Fig. 1.—Benham's Disc

Although the Arab Alhazen, as early as A.D. 1000, knew a great deal about the properties of light, he could only speculate vaguely that vision is due to "rays" of light or "radiations", which reach the eye from external objects, and it was not until the time of Huygens that the first ideas of the "wave theory" of light were introduced. Huygens conceived the whole of space to be filled with an elastic invisible substance which he called the ether; the vibrations set up in this medium by luminous

¹ "Visual diffusivity", see Ives, *Phil. Mag.*, XXXIII, 1917, p. 18.
(L 222)

bodies were the "waves" of light. Such vibrations spread out into the surrounding regions in all directions, in a similar manner to the well-known spreading of the ripples on a pond when the surface happens to be disturbed at any point. Of course in the case of light the wave motion is not limited to a plane surface, but the wave fronts must be conceived as spherical.

It is perfectly true that such a simple "wave" theory is quite inadequate to explain many of the more subtle connections of light with electricity, magnetism, and gravitation, of which so much has been heard of late, but nevertheless the wave theory (as developed by Fresnel) was found adequate to explain the vast majority of the ordinary phenomena of optics. Even at the present day it is being employed to predict and explain many phenomena in the action of lenses, and that with exact numerical accuracy. It is by no means necessary to formulate any exact suppositions regarding the nature of the ether or the waves for such purposes; we shall thus take the wave theory as a phase of the truth, and as entirely adequate for the present subject.

The phenomenon of *hue* is ascribed to the relative frequency of the light vibrations. If we revert to the idea of the ripples in the pond, we may consider a single source¹ of light as similar to a stick shaken quickly in the water surface, from which many ripples close together are spreading out. If the stick be shaken more slowly the distance between the ripples becomes greater, although they still move outwards with the same velocity. The distance from crest to crest of the ripples is termed the *wave-length*, and it is clear that a lower frequency corresponds to a greater wave-length. In the case of the light vibrations the displacements take place perpendicular to the direction of propagation, and in unpolarized (ordinary) light the vibrations are in all possible directions consistent with the previous condition.

It will be necessary in the present discussion to refer often to the "wave-length" of light. It is by no means very difficult to make a measurement of this quantity: for the green light of the spectrum it is found to be about $\frac{1}{48000}$ of an inch or about half a thousandth part of a millimetre. For red light it is rather greater, and for blue light rather less than this amount.

It is found that the sensation produced by a definite wave-length of light is a fairly constant thing, at least under normal conditions

¹ Any ordinary source of light contains myriads of particles which might be regarded as single sources.

of vision. Inasmuch as it is hardly possible to measure or even to describe a sensation apart from the exterior physical conditions which may cause it, no apology will be made for the introduction of the ideas of *wave-length* and *intensity of vibration*, as they are the only measurable and realizable properties of light which we can link on (as causes) to our subjective experiences.

Furthermore, a moment's thought will show that since *light* is the intermediary between object and eye, it will be necessary to discuss the properties of light before the colour properties of objects are considered.

Ray Paths in Prisms and Lenses.

The great philosopher Newton was well aware of the wave theory of light, but the mathematics of the subject seemed to him to lead to erroneous conclusions, and he was unable to accept it. He knew

that light, generally speaking, travels along straight lines, and he based his corpuscular theory on such a conception. Nowadays we think of a "ray" of light as the path of a wave disturbance, which is naturally always perpendicular to the wave itself. Nevertheless the idea of the ray is very useful. Thus, for example, when a ray

enters a denser medium (such as glass) from air we know that it is bent towards the normal to the surface (see fig. 2). The different wave-lengths (corresponding to different hues) are bent by differing amounts, the

shorter wave-length always suffering the larger deviation. The path of the light is reversible; thus on passing from *glass* to *air* the deviation is always away from the normal, and the rays of shorter wave-length are again deviated to a greater extent. By causing the ray to pass through a prism (see fig. 3) we can investigate the final paths of the rays by receiving the light on a screen. It is again

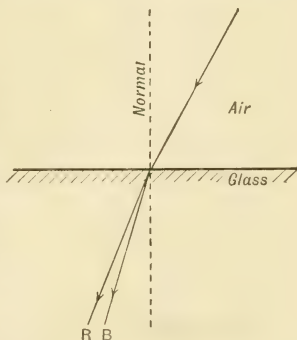


Fig. 2.—Refraction of Ray

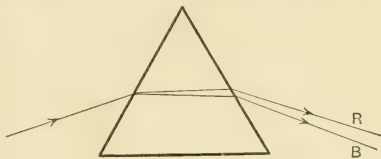


Fig. 3.—Action of Prism

found that the rays of shorter wave-length, typified by B (blue) in the diagram, are more deviated than those of long wave-length, typified by R (red), the deviation being additive at the two surfaces. This unequal refraction of different hues is called "dispersion". The amount of dispersion is exaggerated in figs 2 and 3.

It is but a step from the idea of the action of the prism to the understanding of the action of a lens, which will obviously produce a similar deviation and slight dispersion in the rays of light. By giving curved surfaces to the glass it is found possible to receive the rays diverging from an object point O (see fig. 4), and bring them together again in a focus O_1 , or very nearly. The rays of

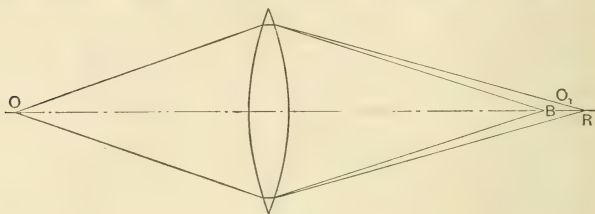


Fig. 4.—Action of Lens

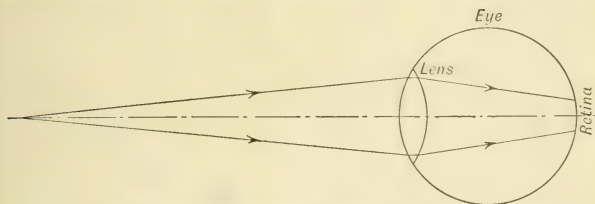
shorter wave-length, however, come to a focus rather nearer the lens unless this is made *achromatic*, by being composed of two or more components of differing types of glass.

Within certain well-known limits every point in the "object-space" of the lens has its corresponding image-point, as the power of focusing the rays is not limited to points on the axis; thus images of definite size are formed, and may be received on a screen in the "image-space", or may be viewed by an eye suitably placed to receive the image-forming rays. At best the brightness of an image so viewed can never exceed the brightness of the object, no matter what optical arrangements are employed.

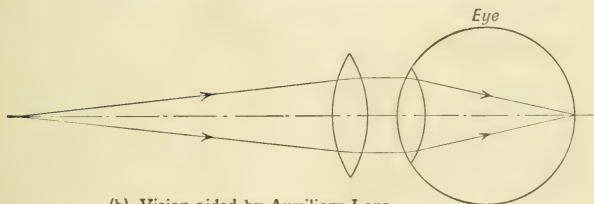
The *aberrations* of lenses are the deficiencies in the ray congruence, which is seldom or never quite perfect. From another standpoint it may be said that the action of the lens should bring all the wave disturbances or vibrations from an object-point into the same phase at one image-point, but in practice there are always residual phase differences. Generally speaking the aberrations tend rapidly to increase if lenses are employed of a large diameter rela-

tively to the focusing distance, or if the image-forming rays make large angles with the axis.

The Eye.—For the present we shall regard the eye simply as an optical instrument, consisting of a lens and an image-receiving screen known as the retina, which is sensitive to light and constitutes the visual receiving apparatus for sensations of light. The focusing distance between lens and retina being constant, the power of



(a) Insufficient Refractive Power. No Focus on Retina



(b) Vision aided by Auxiliary Lens

Fig. 5.—Action of Auxiliary "Magnifier"

accommodation is secured by muscular actions, which change the curvature of the surfaces of the lens.

Increased curvature results in the greater deviating power of any zone of the lens for a ray of light, and permits of the focusing of rays diverging from nearer points.

The same effect is secured by employing a supplementary magnifying lens or eyepiece; the use of such an optical aid held before the eye permits of the object under observation being brought much closer to the eye than would otherwise be possible (and therefore appearing much larger or more magnified). The diagram (fig. 5) will assist in the understanding of the action. Perhaps it should be stated, too, that a lens of given curvature has no more than a certain deviating or "collecting" power. When the possible

increase of curvature in the lens of the eye fails, a supplementary lens has to be employed to focus nearer objects.

This résumé will be sufficient for the purpose of any reader who, while not familiar with the elements of optics, nevertheless desires to know something of the optical investigations on which the physical study of colour must be based.

Newton's Experiment.—It was remarked that Newton was unable to accept the wave theory. He was able, however, to lay the foundations of modern spectroscopy by his experiments on the dispersion of light, and a repetition of a similar experiment with somewhat modified apparatus (see fig. 6) will be extremely instructive.

Light from a small arc lamp A is focused on a slit S, which may be 2 to 4 mm. in width and 15 mm. long. Some of the light passes

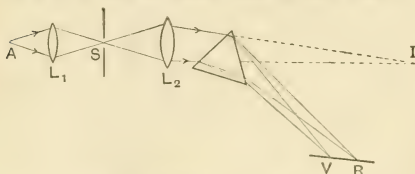


Fig. 6.—Formation of a Pure Spectrum

on through the slit and diverges on the other side only to meet the lens L₂. (It is convenient to use a photographic camera lens of focal length 6 to 8 in.) This lens is so placed that it

forms a white image I, which can be found on a screen and focused at a distance of about 15 ft. Stray light should be screened off.

A hollow prism, with a refracting angle of about 60° and containing carbon disulphide, may then be placed in the path of the beam, as indicated in the diagram, and turned so that the *deviation* produced is a minimum. It will be found that instead of a white image we have a brilliantly coloured band of light in a new position, but at about the same radial distance from the prism.

Newton's work was done with beams of sunlight. He showed that not only does the prism thus disperse the white light, but that greater deviation is always produced by the prism for the pure blue light of the spectrum than for the green, or other longer wavelengths. If we desire to isolate any special region of the spectrum for experiment, we may follow his example and make an aperture in the screen at the place on which that light is focused.

Six very distinct hues are noticed, red, orange, yellow, green, blue, and violet, at least by a person with normal vision, and these hues fade gradually one into the other with imperceptible steps. The source gives, in fact, a *continuous spectrum*, and we may consider

that a separate image of the slit is formed for each wave-length present—an infinite number of images corresponding to the infinite number of infinitesimal steps that may be considered to lie between the two wave-lengths marking the ends of the visible spectrum. Care must be taken to guard against the idea that the spectrum is composed of a certain number of homogeneous sections. This is not so; change is continuous all the way through.

It is true that we can, if we so desire, use a source not giving a continuous spectrum but radiating light having a limited number of definite frequencies, when a *line spectrum* is the result. A “mercury lamp” placed in the position occupied by the arc of fig. 6 will give this effect. An image of the slit having a width in a definite proportion to the original is then found for every frequency or wave-length of light present.

It will be clear then that, in order to secure purity of the colours of the continuous spectrum, the image of the slit for any definite wave-length should be narrow in relation to the length of the spectrum, otherwise serious overlapping of the different colours is inevitable.

It has thus been shown that white light may be dispersed into constituents which cause various colour sensations when received on the retina. It is no less instructive to make use again of the well-known collective power for rays, which has been seen to be possessed by a lens, and thus to collect the dispersed light together once more. When this is done it is found that the brilliant hues vanish and that white light is formed.

These experiments should teach us that “light” is the source and origin of colour, and this fact may be conveniently illustrated by a few additional simple experiments to be performed while the continuous spectrum is available.

Selective Reflection and Absorption.—It will obviously be of interest to select variously coloured substances and illuminate them by pure spectral lights, in order to study the effects produced. We take, for example, a piece of red coloured wool and take care to shield it from all stray white light while holding it in the focused spectrum. In the red it is found to appear red as usual, and comparatively bright, but on moving it into the yellow region its brightness fades and it appears dull brown. In the green it becomes apparently quite black, and remains so in the blue and violet regions.

The explanation of this is that the wool absorbs the light energy

in all spectral regions except the red, but reflects red light. When placed in white light it has the power of selecting the red light, which we have learned to regard as present in the white, and *reflecting* that alone, while absorbing the remainder of the constituents; hence its "red" appearance.

Similarly a piece of green wool reflects well only in the green region of the spectrum. In the violet and red it appears quite dark, although possibly reflecting a little.

A piece of magenta material should be of interest in this connection, because it will be noticed that, although the spectrum contains most of the known hues, it does not contain purple, violet being the nearest approach. The magenta substance, however, is found to reflect brightly in the red and blue-violet regions, while absorbing strongly in the yellow and green.

Many interesting experiments with light filters (coloured glasses, &c.) may also be made. Red glass, for example, when held in front of the slit, leaves only the red part of the spectrum (in the same position on the screen) and also grows hot, thus showing that the energy of the other wave-lengths has been absorbed and transformed into heat.

Fluorescence.—It will soon be found that the majority of substances produce no change in the hue of the light which falls upon them, but merely alter its intensity by more or less absorption. This is not the invariable rule, however, for certain dyes will be found, such as rhodamine, which can absorb light in all the visible spectral regions having wave-lengths shorter than the yellow, and re-emit it as yellow. A screen of barium platino-cyanide, as used in X-ray work, gives a brilliant exhibition of this effect, which is known as *fluorescence*.

Many bodies fluoresce with light of other hues than yellow. For further details of this interesting subject textbooks on physical optics should be consulted; but we may merely notice here that when white light illuminates a fluorescent substance it may easily appear to reflect more of its characteristic colour than would be possible even to a perfectly reflecting material, owing to this power of transmuting the energy of the shorter wave-lengths.

Ultra-violet and Infra-red Regions of the Spectrum.—In making experiments with a fluorescent screen, it is easy to show that brilliant fluorescence is caused when the screen is moved beyond the violet end of the spectrum into a region where no light is visible to the eye. This region of invisible energy can also affect a photo-

graphic plate, and a great deal has now been learned about the properties of these radiations by photographic methods.

It is found that the ultra-violet waves, when sufficiently intense, have extremely strong chemical and electrical effects, and on this account it is found necessary to protect the eyes when using certain sources of light (such as an unscreened arc lamp) or in oxy-hydrogen blowpipe welding operations.

The really dangerous portions of the radiation are partially screened by a thin plate of ordinary glass, but it is, of course, always necessary to protect the eyes from the intense visual brightness of unscreened sources by dark glasses or otherwise. The question of harmful ultra-violet radiations does not often arise, and in most of the ordinary artificial lights the intensity of the ultra-violet is very small in comparison with its intensity in daylight. Even in daylight any possibly harmful radiations from the sun are now known to be screened off by a kindly veil of ozone in the upper atmosphere, so it would appear that those finding trouble from glare in daylight would be better advised to wear "neutral" glasses to diminish the intensity of the light, rather than to experiment with spectacles possessing wonderful properties in screening off the harmful rays, which have already been largely removed by nature.

Energy may also be found beyond the red end of the spectrum, but its chemical and electrical effects are comparatively very small. If a very sensitive instrument to indicate "heating effect" is placed in the spectrum of an artificial source of light, it will be found that a rise of temperature is always consequent on the absorption of light, but it will also be found (in most cases) that the heating effect is a maximum beyond the red in a region where no light is visible. Extensions of such experiments prove that visible light corresponds only to a small part of the range of possible wavelengths in the same type of ether radiations. The shortest waves known are the "X" and similar rays, and the longest are those employed in wireless telegraphy.

Colour in Nature.—Nature has many ways of eliciting hue other than those we have touched on. The colours of a soap bubble and the gorgeous tints of the sunset are produced in very different manners, but in every case where we have daylight as the original illuminant the hue is the result of the loss or scattering of some of the components of white light. The glowing red of a fire arises differently, of course, as the fire is really sending out much more red light than green and blue, although these shorter wave-

length components may not be wholly lacking. If we could heat up the fire indefinitely, the light it gives would be whiter and whiter until, when its temperature was equal to that of the sun, we should not be able to distinguish the hue of the light from that of sunlight. We cannot attain such high temperatures at present in ordinary sources of light, and consequently we have been unable to produce an illuminant the light of which appears as white as sunlight.

Hue and Wave-length.—By certain physical methods the wave-length of the light vibrations may be measured in terms of our ordinary units of length, such as the centimetre. As the wave-length is so exceeding small, however, we shall use the one-thousandth part of a millimetre as a convenient unit of length, and we shall term this unit μ .

$$\mu = \frac{1}{1000} \text{ mm.}$$

There appears no reason to doubt that light of a particular wave-length gives very much the same type of sensation to the majority of human beings.

A very convenient method of describing a hue sensation is by implicit reference to the region of the spectrum giving the sensation most similar. Thus, even if we vaguely describe a colour as blue, we are referring to a particular quality of "blueness", which we learn to distinguish under all degrees of modification and dilution, but which is only found more or less ideally as the sensation given by a small range of wave-lengths in the spectrum.

The number of different hues which can be distinguished in the spectrum is a matter of some controversy. There is, however, little confusion in the broad nomenclature of the hue sensation derived from particular ranges of wave-length. In the following table the divisions given by (1) Abney and (2) Listing are set out.

(1) ABNEY					(2) LISTING	
Red ..	..	End	to	$\cdot 62 \mu$		$\cdot 723 \mu$ to $\cdot 647 \mu$
Orange	..	$\cdot 62 \mu$	„	$\cdot 592 \mu$		$\cdot 647 \mu$ „ $\cdot 585 \mu$
Yellow	..	$\cdot 592 \mu$	„	$\cdot 578 \mu$		$\cdot 585 \mu$ „ $\cdot 575 \mu$
Green	..	$\cdot 578 \mu$	„	$\cdot 513 \mu$		$\cdot 575 \mu$ „ $\cdot 492 \mu$
Blue-green	..	$\cdot 513 \mu$	„	$\cdot 500 \mu$		—
Blue ..	..	$\cdot 500 \mu$	„	$\cdot 464 \mu$		$\cdot 492 \mu$ „ $\cdot 455 \mu$
Ultramarine	..	$\cdot 464 \mu$	„	$\cdot 446 \mu$		$\cdot 455 \mu$ „ $\cdot 424 \mu$
Violet	..	$\cdot 446 \mu$	„	End		$\cdot 424 \mu$ „ $\cdot 397 \mu$

Five *very* distinctive hues, red, yellow, green, blue, and violet,

are found, while the remainder are apparently related to these, and the recognition of the relatedness appears to be almost instinctive. By special optical means, however, two patches of light of slightly differing wave-lengths may be brought into juxtaposition in order to render any perceptible contrast of hue more easily recognizable. In such a way it has been shown that, to a person with normal vision, the number of quite distinct hues in the spectrum is in the neighbourhood of 128 (between $\cdot 4 \mu$ and $\cdot 7 \mu$). Lord Rayleigh claimed to be able to distinguish the difference of hue between the two sodium lines ($\cdot 5890 \mu$ and $\cdot 5896 \mu$), but many will find this hard to believe, as slight intensity differences are easily mistaken for hue differences. Different methods of comparison lead to widely different results in this investigation.

The range of hues known as the purples may be formed by the union of spectral red and blue, and give another twenty distinct hue sensations which are not found in the fundamental hues of the spectrum.

Definitions.—We will close the present chapter by an attempt to supply some definitions of certain of the terms which will be frequently employed.

The widest use of the term “colour” implies that colour differences include differences of brightness or luminosity; in fact, a definition may be formulated as follows:

Colour is a term given to the sensations due to those qualities of light by which an eye may recognize the form and nature of an object.

Colours are said to differ in hue, in saturation or purity, and in brightness. “White” will merely find its place in the whole continuum of colour, and “black” is the negation of colour.

White is the colour of sunlight passing through a minimum thickness of the earth’s clear atmosphere, and this sensation is not caused to normal-sighted persons by light of any single wave-length. From ordinary experience of nature we constantly learn the effect of the admixture of white light with light of other colours.

Hues are characteristics of colour sensations by which these may be distinguished, apart from their brightness or whiteness. Thus “white” is a colour but has no “hue”. “Hue” generally appears when some of the wave-length constituents of white light are removed.

The presence of a definite hue may be recognized in the coloured light derived from a multiplicity of objects, and similar or allied hues are often grouped under one name, like ‘blue’, which really covers a wide range of sensations.

The saturation, purity, or chroma of a colour refers to the proportion of the brightness of the pure hue sensation to the total brightness of the colour. The brightness of coloured light may be assumed to consist generally of two parts: (1) the brightness of the component which also causes the pure sensation of hue, and (2) the brightness of any white sensation which may be present.

The discussion of the exact meaning which we shall attach to the phrase "brightness of a sensation" must be deferred to a later chapter. At this stage it will be sufficient to catch the general idea. It will be noticed that it is necessary somewhat to restrict the use of the various terms employed. In fact, the term "hue" will generally take the place of the term "colour", as commonly used, when we wish to distinguish the property of a sensation which is its non-whiteness. The advantage of this is that we are thus allowed to call yellow and brown different "colours" quite legitimately, although they may possess the same hue. Evidently the use of the term "colour" in ordinary speech is far too inexact, and the loose use of the terms colour and hue leads to confusion in scientific work.

Having formed the conception of a pure hue (which may or may not be found quite ideally in the spectrum), we may now conceive a wide range of perceptibly differing colours formed from it, for we might proceed to dilute the hue with differing amounts of white (keeping the total light always to a standard intensity), and thus forming a *tint* series or series of differing saturation. Further, with any member of the same series the "brightness" may be varied from zero upwards in a great number of perceptible steps until a "dazzling" brightness is reached. This produces a series of *shades* of a pure hue. For any hue then we have a kind of two-dimensional variation; and a three-dimensional variation appears when a range of hues is considered.

The term "tone" includes any variation of saturation or brightness while the hue remains constant.

The term "value" is one used by artists to denote the brightness of a colour, but this brings us to an important point. We have, so far, merely defined our terms as relating to "coloured light". It is evidently necessary to modify the definitions somewhat when dealing with coloured substances; but it will be sufficient at present merely to remember that we then give *relative* specifications of colour and its variables (hue, saturation, and brightness).

The intensity of light is capable of an infinite range of variation,

but when it is desired to find the apparent brightness of a reflecting material substance under definite conditions of illumination the reflecting power or coefficient of reflection must be known. Hence, when specifying the colour of a substance which reflects and diffuses light, the hue and saturation of the reflected light are given as before (under the assumption that the illuminant is to be white light), and the other quantity must now be the ratio of the brightness of the reflected light to that which would be derived from a perfectly reflecting and diffusing substance placed under the same conditions. A similar proviso applies to cases where the colour is seen by transmitted light. It is suggested in America that the term "brilliance" be used to denote the above ratio. Here the tint series must end with "white", each member of this series giving a "grey" series through brightness variation, with black at the bottom of all of them. This subject is considered in Chapter III. The definitions have to be modified when the substances do not diffuse the light, as colour may then change with the direction of view.

CHAPTER II

Colour Analysis and Synthesis

A great many difficulties in colour measurement and nomenclature have arisen through lack of appreciation of the central fact that the apparent colour of a material body depends on the quality of the light by which it is illuminated. We shall postpone the particular consideration of "coloured materials" and deal for the present with coloured light alone.

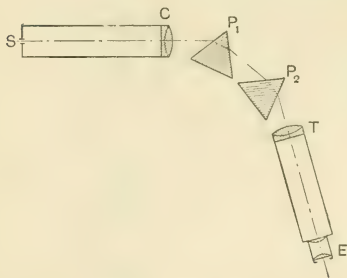


Fig. 7.—Spectroscope

The Spectroscope.¹—

We have reviewed in the previous chapter a method by means of which coloured light may be analysed, and the spectroscope is merely a development of the apparatus described. It consists of a slit S (fig. 7) placed at the principal focus of a "collimator lens" C. Light diverging from S and passing through C produces a parallel beam which passes through one or

more dispersing prisms P_1 and P_2 ; and finally the telescope objective T brings the spectrum to a focus in such a position that it can be examined by an eyepiece or magnifier E. Here, then, is an apparatus by which coloured light is analysed—simply in terms of wave-length.

If we examine, for example, the light from a sodium flame we shall find the spectrum to consist of two lines very close together

¹ Non-optical students will find it well worth while to read through the description of apparatus given in the first sections of this chapter, although they will require only general ideas of these matters.

in the yellow-orange. There is another fainter line in the violet which is generally not visible

The spectrum of the light from a mercury vapour lamp also consists of a number of bright lines, and details regarding certain other line spectra will be found in the Appendix.

The light from many incandescent bodies, however, when examined by the spectroscope is found to give a more or less continuous spectrum. This was noticed when the experiment of forming the spectrum from the light derived from the crater of the arc lamp was performed.

It will be noticed in comparing the continuous spectrum of the arc crater with that from the flame of an oil lamp that the relative intensity of the violet end of the spectrum, as compared with the red, is much less in the case of the flame. Hence the spectroscope permits the qualitative, and to a limited extent an approximate quantitative analysis of visible light. Certain additions to the

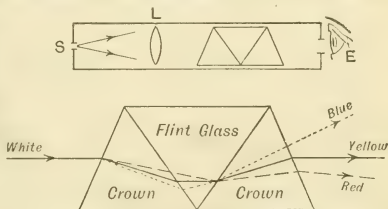


Fig. 8.—Direct-vision Spectroscope and Prism. The dispersion is greatly exaggerated

ordinary spectroscope are necessary if a satisfactory quantitative analysis is to be made; these transform the spectroscope into the "spectrophotometer", an instrument which will be described later.

Direct-vision Spectroscopes.—There are other convenient forms of spectroscope which merit a brief notice, the chief of these being of the "direct-vision" type. These instruments employ a compound prism, in which dispersion is secured by the different dispersive powers of crown and flint glasses. At the same time the angles are so calculated that some mean ray of the spectrum suffers no deviation (generally the yellow).

Fig. 8 illustrates the construction of such a direct-vision spectroscope and also the action of the triple prism.¹ Three parts are used in order to obtain greater dispersion, but a simple doublet (half the triple prism) can be used. The deviation of the rays is shown in the diagram.

It should be noticed that the shorter wave-lengths are deviated

¹ Even greater angles are used in the prism. The dispersion is purposely exaggerated in the figure.

towards the base of the flint-glass prism, which possesses the greater dispersive power. Note also that in the ordinary type of direct-vision spectroscopy the light diverges from the slit *S*, is collimated or rendered parallel by the lens *L*, and dispersed by the compound prism. The refracting system of the eye projects the image of the spectrum on the retina.

Fig. 9 is intended to show how the dispersed "bundles" of parallel rays, issuing from the aperture of the direct-vision spectroscopy, are focused by the lens of the eye to form a spectrum on the retina.

"Diffraction gratings" also produce the dispersion and deflec-

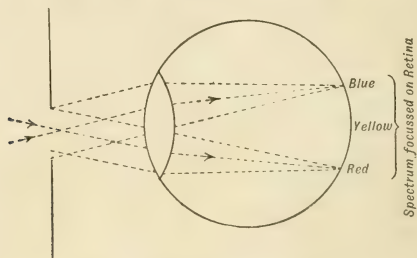


Fig. 9.—Spectrum formed on Retina

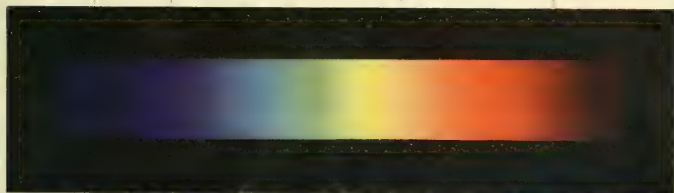
tion of a part of the light passing through them, and may be used as the dispersing units in spectroscopes. They will be described later.

Selection of Particular Wave-lengths.—By reference to fig. 6 it will be easily understood that light comprising only a small range of wave-length may be isolated by placing a screen with a slit aperture in the plane of the focused spectrum. Small and convenient instruments are made for this purpose, and are known as monochromators.

Additive Mixing of Coloured Lights (Experimental Method).—If the experiment of collecting and mixing the coloured lights of the complete spectrum on a screen has been performed, the consequent reappearance of white will be remembered, and this is the first item in the series of facts regarding the mixture of coloured lights which must now be noted.

We should now consider the possibility of isolating and mixing the light corresponding to smaller ranges of wave-length in the

A NORMAL CONTINUOUS SPECTRUM



·4

·5

·6

·7



ADDITIVE COLOUR MIXTURE



SUBTRACTIVE COLOUR MIXTURE

spectrum, and for experimental purposes it is naturally desirable first to form a spectrum and then to select from it various regions, the light of which we may desire to use.

For lecture demonstration this is best done by means of an apparatus similar to that employed by Professor Cheshire. (Figs. 10 and 11 show the arrangement.)¹

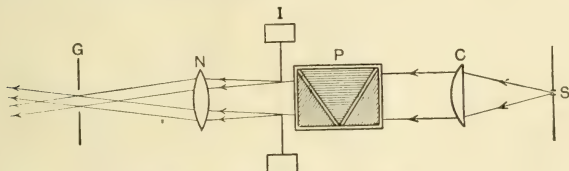


Fig. 10.—Colour Mixture Apparatus Plan

The essential feature of the apparatus is really the direct-vision spectroscopy system formed of the slit S, the collimator lens C, the prism (compound) P, and the lens N, which forms a spectrum in the plane of the aperture G.

I is a circular iris diaphragm placed close against the prism face, and this may, of course, be varied in aperture at will.

Not only does the lens N focus the spectrum, but it also projects an enlarged image of the circular aperture I on a screen at some

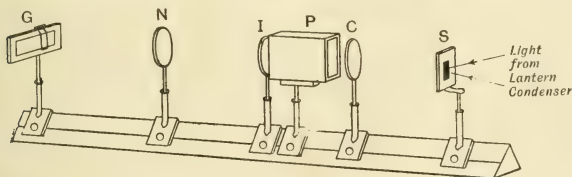


Fig. 11

distance, which may be viewed by a class. The screen (not shown in the diagram) may be imagined some distance away to the left.

Now although the various wave-lengths are separated at G, the aperture I is small enough and sufficiently close to the prism face to receive a full beam of every hue.

Therefore, since the lens N is forming an image of an aperture

¹ The bench and fittings shown in the sketch are manufactured by the Ocentric Optical Company. The compound prism contains liquids, and has an aperture of about $2 \times 1\frac{1}{4}$ in.

illuminated by white light, the image on the screen will be white. The fact that during their path to the screen the differently coloured rays from any point of the aperture follow different paths and happen to form a spectrum *en route*, does not affect the validity of the argument.

By placing one or more small prisms¹ in the spectrum, however, it is possible to deviate some of the coloured light, so that two or more images of the circular aperture are formed on the screen, and it is easily possible to select prisms of such an angle that the images of the discs are separate when the diaphragm is small, but overlap when this is enlarged.

Additive Mixing of Coloured Lights (Experimental Results).—The apparatus described in the foregoing section gives us, then, the means of separating the image of a white patch into two patches, one illuminated by the wave-lengths in the light comprising one part of the spectrum, and the other by light corresponding to the remaining portion. Again, by the use of two prisms, we may divide the spectrum into three regions, producing one direct image and two deviated images illuminated respectively by three distinct groups of wave-lengths in the spectrum.

It will not be difficult to show that (as we should expect from the foregoing work), when two images only are formed and made to overlap, the union of the two colours produces white. A range of hues may thus be found the members of which form white with corresponding members of another range.

When three images are formed it may be arranged that they are red, green, and blue-violet in colour. When they are made to overlap, scattered light from any two (or from all three) reaches certain portions of the retina as an additive mixture.

It is then found that:

Red	light	+	Green	light	=	Pale yellow	light.
Green	„	+	Blue-violet	„	=	Blue	„
Blue-violet	„	+	Red	„	=	Magenta	„

Where all three patches overlap it is seen that white is produced.

Not only do we infer that red, green, and blue-violet when mixed together produce white; we are evidently mixing also composite lights of hues expressed as pale yellow, blue, and magenta, which mixture is also giving a white. It will be generally found

¹ Small skew prisms of 3° to 5° angle are suitable.

that the additive mixture of coloured lights tends to give increased brightness, with a tendency to the destruction of saturated hues and the formation of white.

Such experiments give no indication of the results of mixing coloured substances, such as paints, but relate only to coloured lights.

Mixing of Monochromatic Lights.—In the foregoing experiment broad regions of the spectrum were selected, and the light from one of these comprises a considerable range of wave-length, though giving necessarily the visual impression of a single hue (more or less saturated) to the eye.

In order to work with more nearly "monochromatic" light it is advisable to use the "colour-patch" apparatus¹ (to be described later in this book), and to employ three fairly narrow slits in the plane of the spectrum. Light from these slits is then mixed on a white diffusing surface.

With such an arrangement the experiment of mixing more nearly pure red, green, and blue-violet lights may be performed, when the same or similar results will be obtained, but the hue of the mixed light will vary with the relative intensities of the components as determined by the spectral intensity, relative dispersion, and slit width. Very delicate adjustment of the widths of the slits is necessary to produce a satisfactory white. It will be found possible somewhat to vary the positions of the three slits in the spectrum, and still to produce a *white* by suitable control of the relative intensities; we can, for example, use one slit in the blue, and move the other two closer together. If, however, we retain the red, green, and blue-violet monochromatic primaries, it will be found possible by suitable mixtures of these correctly to produce *any* known *hue*, although not necessarily to match any *colour*, as the latter would involve all possible adjustments of saturation and brightness, and the combination of the primaries will contain more white than some of the pure spectrum colours. Many colours, however, *could* be accurately matched.

Trichromatic Theory.—The possibility of the synthetic production of such a wide range of hues has led to the theory that there are three types of colour receptors in the retina which give rise, when stimulated singly, to red, green, and violet sensations respectively. Stimulation of all three in suitable relative intensities is

¹ It gives a much bigger spectrum, and "little bits" may be selected more conveniently.

supposed to produce the sensation of white. By the labours of Helmholtz and later workers the relative stimulation of these theoretical primary sensations by the colours of the spectrum has been measured numerically, and it has been shown that some ranges at least of the visible wave-lengths of light are capable of stimulating all three sensations, or, in other words, those spectral colours give *some* white sensation. The presence of white sensation in the spectral green is supposed to account for the paleness of the yellow which results from the additive mixing of red and green. On this theory it is supposed that a normal eye never sees green at such a full saturation as is possible with red.

Complementary Hues.—For light of any colour (even “monochromatic” light), a complementary colour may be found, which, when added to the first in the correct intensity, will produce white. It is found that for most regions of the spectrum the hue of the complementary is itself a spectral hue. This is exhibited in the following table.

TABLE OF COMPLEMENTARY HUES

Red	·656 μ	and Bluish-green	·492 μ
Orange-red	·608 μ	„ Blue-green	·490 μ
Yellow	·585 μ	„ Blue	·485 μ
Yellow-green	·574 μ	„ Ultramarine	·482 μ
Greenish-yellow	·564 μ	„ Violet	·433 μ
Green (regions between and ·492 μ)		Purples (not found in the spectrum but formed by red and violet)	

It is obvious that a colour resulting from the addition of white to a complementary hue is also a complementary.

Colour Discs.—It is realized that, especially to a student who has not access to the apparatus necessary to study the subject of colour analysis and synthesis experimentally, the foregoing descriptions and discussion may be somewhat difficult to follow. Nevertheless such a one should make an effort to construct a rotating disc for colour mixture, sectors of which may be variously coloured with suitable pigments (see fig. 12). Whole discs of thin card should be coloured; vermilion, emerald green, and ultramarine make suitable pigments which are stable and good, but more brilliant although temporary effects can be obtained by the use of the Kodak Company's water-colour dyes, put up in convenient “book” form for tinting photographs. Each disc has a central hole and a radial slit; thus two or three discs may be threaded together and rotated by

a small electric motor or hand-whirling table. Although this mental or "nervous" mixing of coloured lights is no true physical mixing, yet the study of the synthesis of hue sensations may in this manner be carried out in an exceedingly instructive manner, if it be remembered that the coloured discs are giving a "range" of wave-lengths and not monochromatic light, and also that most pigments reflect a considerable amount of "white" light.

Colour Mixture by "Overlapping".—Coloured objects or "patches" may be of such small dimensions that their images cannot be seen separately or "resolved" by the eye, and in this case their colours are mixed by confusion on the retina.

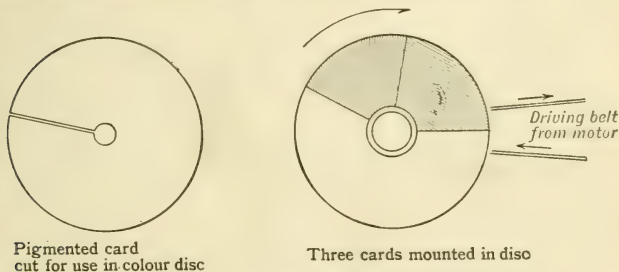


Fig. 12.—Colour Disc

Such a mixing is employed in certain processes of colour photography, such as the autochrome process, where (for example) yellows are rendered by the confusion of the retinal images of minute red and green starch grains. Painters sometimes use this "confusion mixing" to produce certain effects, particularly when great luminosity is required.

There is another queer type of mixing which can be performed by holding a red card in front of the left eye about six inches away and a green card in front of the right eye. A mental overlapping of the images can thus be produced, but it is exceedingly difficult to describe the resulting sensations. With black-and-white objects it may easily be verified that, should the retinal images be incapable of "fusion" to form a complete whole, the recognition of one seems to inhibit the recognition of the other. Much the same applies to the mental overlapping of colour sensations; it seems often impossible to recognize any stable character of the mixed impression; either one colour or the other seems to pre-

dominate except in some cases, as when a red and blue are superimposed, and there is (to the writer) a suggestion of purple in the resulting sensation. A paper by Rivers on "Binocular Colour-mixture" may be consulted for further details. See Camb. Phil. Soc., Vol. VIII, p. 273.

Chromoscopes.—It is possible, by using a sheet of plane glass, to view in apparent superposition colours seen respectively by reflection and transmission of light. Such a device affords a very simple means of mixing coloured lights, and has been applied in instruments known as *chromoscopes*, where, by similar means, the images of three transparencies representing the same subject and illuminated by light passing respectively through red, green, and blue-violet coloured filters, can be optically superposed (p. 166). The exact arrangement varies between different instruments, and in at least one case the subjective or mental mixing to which reference was made in the previous paragraph is employed to combine two coloured images. The colour mixture seems to be satisfactory, and the conditions lend themselves to the production of stereoscopic effects.

CHAPTER III

The Colours of Material Objects: their Nomenclature and Measurement

The Colours of Objects.—It has been shown that hue sensations are caused by light which is lacking in some spectral components which would, if also present, give a combined sensation of white. When light falls on a material substance it may undergo reflection at the surface, and also it may be transmitted with or without absorption. Also in some cases light is reflected from layers of the material slightly within the surface, and if the substance has a high selective absorption this reflected light may give a marked hue sensation. It is in this way that the various colours of opaque objects arise. Very often all the possibilities are realized, surface reflections, transmission, and absorption all taking place to a measurable extent.

Very often there is a considerable amount of white *unaltered* light reflected from the outermost surface, and if it is diffusely reflected the colour of the whole reflected light appears to be less saturated in colour (provided that white light is being used as the illuminant). If, however, the surface of the material is regular and polished the reflection is said to be specular, and in this case the surface light (if incident from a source of limited area) may be reflected entirely in a given direction, whereas the components which have undergone selective absorption in the outer layers are often still radiated diffusely, and may reach the eye when this avoids the specularly reflected light. In such a case the colour appears much more saturated.

The well-known differences in the appearance of polished and unpolished wood may be cited as an instance of the foregoing effects.

The nature of the surface, again, has much influence on the

apparent colour. If the surface is rough or finely divided, it may produce multiple reflections between the particles, and thus appear of a perceptibly different colour from that which it possesses when the surface is smooth.

Colour Filters.—The colours of light which arise by transmission *through* “coloured” objects are the consequence of simple selective absorption. They depend, naturally, on the thickness of the coloured material. Unit thickness of the material may be regarded always as absorbing a percentage of the energy which is constant for a particular wave-length, but in some cases if the percentage absorption is very different for different regions of the

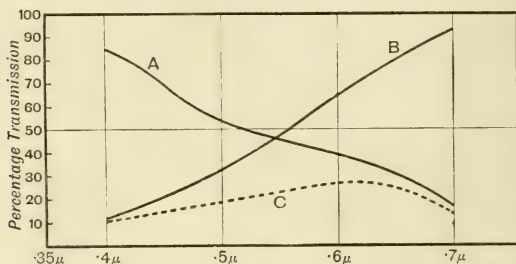


Fig. 13

A, Transmission Curve for First Filter. B, Transmission Curve for Second Filter.
C, Transmission Curve for Two Together.

spectrum there are perceptible hue changes with increase of thickness; for the sensation received by the eye depends not so much on the presence of certain spectral components as on their *relative* intensities, which will vary with a greater thickness by reason of the absorption. This is called *dichroism*.

Generally speaking, however, the *hue* remains fairly constant, while the *saturation* increases with the thickness. In virtue of the action of selectively transmitting bodies in “filtering out” special components of light, they are often known as “light filters”.

Having given the transmission coefficient x of a light filter (the fraction of the light energy transmitted) at any wave-length, and the coefficient y of another filter for the same region, the coefficient of the two when combined so that light passes through the two in series is evidently $x \times y$. Thus if one filter transmits $\cdot 7$ or 70 per

cent (at wave-length $\cdot 5 \mu$ say), while another transmits $\cdot 3$ or 30 per cent at the same wave-length, a fraction $\cdot 21$ or 21 per cent of the total light will be transmitted by the two. (See fig. 13 for the derivation of the transmission curve of two filters placed together.) The ordinate of the curve C at any wave-length is the product of the ordinates of A and B.

By means of a spectrophotometer the transmission coefficients of a filter may be found for a series of wave-lengths throughout the spectrum, and a transmission curve may thus be plotted. If such a transmission curve for a second filter is supplied, a simple series of calculations on the above lines will furnish the curve for the two when placed together. Spectral transmission coefficients may also be measured conveniently with the colour-patch apparatus to be described in a later chapter.

It will be clear that such a transmission curve expresses quite definitely a physical property of the transmitting body which does not depend on the nature of the illuminating light, and it may now be more clear that a colour filter simply modifies the distribution of energy in the spectrum of transmitted light; we cannot, therefore, know the nature of the transmitted light until the nature of the original light is specified. In other words, *the apparent colour of the body depends on the light as well as on the properties of the substance*. An algebraic discussion of absorption is given in the Appendix, Section I.

Dichroism.—Dichroism or dichromatism is apt to arise when a substance or solution has a strong absorption band in some region of the visible spectrum. Imagine that a dye transmits fairly freely in the extreme red where the visual luminosity of light is small; also let it absorb very strongly in the yellow and green but have an increasing transmission towards the indigo region of the spectrum, whence the absorption again increases. This represents approximately the case of rhodamine pink, which, in thin layers of solution, has a blue-pink tinge, owing to the fact that the visually brightest part of the transmitted light lies in the green-blue regions of the spectrum. At a greater thickness the more rapid absorption of the blue comes into evidence and the red is relatively much more prominent, a pure scarlet being finally produced.

The most common examples of dichroism are found amongst the aniline dyes. A few cases are given by Paterson,¹ amongst which are:—

¹ *The Science of Colour Mixing*, Scott, Greenwood & Son, 1900.

Substance in Solution.	Hue.	
	In Thin Layer.	In Thick Layer.
Magenta	Bluish pink	Red.
Cochineal carmine ..	„	„
Eosine pink	Rose pink	Scarlet.
Gamboge	Yellow	Orange.
Bichromate of potash	„	Deep orange.
Chromic chloride ..	Green	Claret red.
Quinoline blue ..	Clear blue	Dark red.
Malachite green ..	Blue green	Reddish purple.

These phenomena are of the greatest importance to the dyer, especially in regard to the dyeing of materials (such as velvet) which possess a *pile* in which the light may suffer internal reflections, and effects may be produced similar to those resulting from an increase of thickness of colouring material. For a striking illustration of this effect R. W. Wood suggests dissolving “brilliant green” and “naphthalene yellow” in hot Canada balsam, from which an acute prism can be formed between two glass plates. The prism appears green, yellow, and red in turn on passing from the edge to the base.

An algebraical discussion of dichroism is given in the Appendix, Section III.

Spectral Reflection of “Coloured” Materials.—We have seen that the colours of materials are the results of selective absorption, and of combined absorption and reflection in the case of more or less opaque materials. In order to investigate the spectral reflection from diffusing surfaces, it is generally necessary to compare the intensity of the reflected light for a series of points in the spectrum with the intensity of the light reflected from some standard white surface—which for the time being may be assumed to possess 100 per cent reflection throughout the spectrum. A correction has to be made if the “white” employed is not entirely free from selective effects (for which it has specially to be tested). For experimental investigations of this nature the colour-patch apparatus is convenient. The usual type of spectrophotometer is *not* found convenient, as the intensity of the reflected light is generally too small, but instruments of the König-Martens type have been employed with success.

The questions of the absolute reflection of such whites, and the correct method of illumination and observation during experiment, lead into somewhat more complex mathematical considerations, and

these subjects are dealt with in an Appendix, together with the more particular consideration of the reflection and absorption effects brought into play when a beam of light is transmitted by a light filter having plane reflecting surfaces. The instruments to which reference is made are also described in a later chapter.

The reason for the constancy of the appearance of many coloured substances under varying conditions of lighting is that in many cases the selective action is very strong and only one region of the spectrum is transmitted well. If the hue is, for example, mainly due to a strong reflection in the red, while absorption is large for the remaining wave-lengths, the substance must appear red as long as it shows colour at all. Similar considerations hold for strong greens, and the like; hue changes are more marked under variations of light when the colour of the material is due to reflection in more than one limited spectral region.

“Subtractive” Colour Mixing and Mixing of Pigments.

—Early experiments in water-colour painting will have made the majority of people well acquainted with subtractive colour mixing. In order to make a simple experimental investigation, the use of coloured gelatine films will be found convenient. Blue, yellow, and crimson filters may be selected, and used in conjunction with the simple apparatus for the projection of a spectrum which was described in Chapter I.

By holding each filter in front of the slit in turn, it will probably be found that the blue transmits violet, blue; and green, but absorbs in the yellow. It may transmit a little red. The yellow absorbs violet and blue, but transmits green and the longer wave-lengths.

The crimson absorbs yellow and green, but transmits all the red and some violet and blue.

Any pair of filters then transmits well only in the spectral region common to both thus:

Yellow and blue	make green.
Crimson and blue	„ purple (red and blue together).
Yellow and crimson	„ brick red.

This is the subtractive mixing of the paint-box, where the mixing of finely divided particles of two colouring materials causes the light to suffer the selective absorption of both.

From the above it appears that we may label blue, yellow, and crimson as “subtractive primaries”. The *ideal* subtractive

primaries would possess well-marked regions of absorption. The blue would absorb the red and yellow completely while transmitting the remainder of the spectral colours; the yellow would completely absorb the blue and violet only, and the crimson would completely absorb the yellow and green. The hues of these subtractive primaries would then be "peacock blue", "chrome-yellow", and "cerise". It is difficult, however, to find satisfactory colouring materials (glasses, pigments, or dyes), with exactly the right type of absorption. Compare the colours of the inks used for three-colour-printing (p. 157).

These primaries, if used in varying saturations and "depths of colour" and taken in differing proportions, will give a wide and almost complete range of hues, saturations, and intensities, from "white" to "black".

Colour Nomenclature and Measurement.—It is usual amongst writers on colour to pour scorn on the complicated colour nomenclature of the English language. A vast range of arbitrary and inexpressive terms is pressed into service to denote variations of colour, and the subject is in the wildest confusion. Even in recalling a few of the varieties of blue—Alice blue, peacock, electric, baby, royal, turquoise, cyan, Prussian, ultramarine, to mention only a few—it will be realized that there is great need for a more intelligible system for use in ordinary conversation. Nevertheless it must be admitted that these names are widespread in common speech, and, though employed with doubtful accuracy, will not readily be supplanted unless by a simple expressive system which may lend itself to use in commerce and art.

Lovibond has devised an apparatus for teaching the simpler names of colours in schools, and the need for education in this respect appears to be pressing, from the point of view of the æsthetic life of the community. The fullest enjoyment of beautiful things is often very dependent on the ability to find words to discuss them, and although at every turn of our lives we are constantly using colours of all kinds, we have scarcely any alternative, when wishing to describe an unusual gradation of a colour, to the mute production of a specimen of it.

There are then *two* outstanding needs: first an efficient and accurate colour *notation*, by which any colour can be exactly defined, or rather denoted, by the least number of symbols; and secondly a consistent *nomenclature*, for use in ordinary speech and writing.

It would naturally be convenient that the nomenclature should

have a simple relation to the notation, which would be mainly employed in commerce.

Requirements of an Ideal Colour Notation.

1. To specify a colour exactly in writing by a few numbers or letters.
2. The interpretation of such symbols should (if possible) not depend on the use of any arbitrarily coloured objects.
3. An apparatus for obtaining or interpreting the symbols should be simple, inexpensive, and easily made all over the world.
4. The symbols should give the possibility of an approximate mental estimation without apparatus.
5. The nature of the illuminating light must be specified or "understood".

Requirements for an Ideal Colour Nomenclature.

1. To employ the least number of arbitrary names.)
2. To link colour variations with easily recognized factors of experience.
3. To be definitely related to a current commercial notation.

At the end of Chapter I the three-dimensional variation of colour in hue, saturation, and brightness was discussed. It is evident that the specification of three numbers representing these "co-ordinates" in accordance with some recognized system would fix a colour completely. It has also been seen in Chapter II that nearly every colour may be synthetically produced by stimulating the retina with red, green, and violet spectral lights in various proportions. Here again three quantities would fix a wide range of colour. A third possibility is found in connection with subtractive colour mixing, as three numbers representing the characteristic scale number of three primary colour filters, to be placed in series to reproduce a colour, allow again of a consistent notation.

Of the above possibilities the first (specification of hue, saturation, and brightness) appears the only one likely to yield a corresponding *nomenclature* which will be intelligible, at least without long experience. The last alternative is almost arbitrary; it will be discussed in dealing with the "tintometer".

Colour Charts.—The most elementary form of colour notation refers to a number or name in a colour chart. These charts are familiar objects, and their use is inevitable for the manu-

facture of pigments and the like, where the intention is to provide a *sample* of some special product. Manufacturers of printing inks have progressed farther in the direction of a formally arranged chart, the catalogue of Messrs. Richardson of Gateshead showing an arrangement in terms of spectral hue, but here again the intention is to give a sample of ink rather than a sample of colour.

Messrs. Ruxton (U.S.A.) have gone even farther. Each spectral hue is shown in three saturations, and each saturation is shown in three degrees of brightness (the diminution of "value" being secured by the addition of black).

The Société des Chrysanthémistes (France) issues a colour chart in which the names of colours are given in four languages.

Now an attempt to employ such charts as these for commercial purposes will quickly reveal definite inadequacies. The need for a very complete atlas will be realized, and also the necessity for the grouping of the colours according to some definite system; for again it will be found that if an entirely arbitrary chart be employed, the notation will be useless to others unless they possess an *exactly similar* chart.

The apparent colour, too, of a substance alters with the nature of the illuminating light. Therefore in specifying a colour the nature of the light must be specified also.

The number of distinguishable colours has been seen to be very large. Therefore it is hardly to be expected that a chart should do more than exemplify definite steps in the colour continuum, leaving the exact location of a colour to be specified as between such and such positions. Where the colour cannot be specified in this way with sufficient accuracy it will evidently be highly desirable to have some scientific instrument to fix it exactly.

The set of coloured cards issued by Ridgway (U.S.A.) may be instanced as a case in which an attempt is made to classify colours according to such a definite system. Thirty-six fundamental hues, including purples, are mixed with 9.5 per cent, 22.5 per cent, and 45 per cent of white, and with 45 per cent, 70.5 per cent, and 87.5 per cent of black. These combinations are further mixed with various proportions of grey, making 1025 colours in all. Thus a series of hues, saturations, and brightnesses or values is provided, and the colour of any material may be specified within certain limits by a position in the scale.

Lastly, the system due to the late Professor Munsell¹ must be

¹ *A Colour Notation*, A. H. Munsell, Boston, 1907 (G. H. Ellis Company).

mentioned. We shall consider the psychological facts on which the system is based somewhat closely in a later section. The Atlas¹ of the Munsell colour system contains fifteen charts coloured by hand in order to illustrate the variation of ten hues in *value* and *chroma*, or in *brightness* and *saturation* respectively: 882 examples of colour are given in all. The merit of the system is that due regard is paid to the variation in value of the saturated hues.

The atlas is at present receiving a critical examination by the Bureau of Standards, and the first part of the work, viz. that relating to the brightness or value scale, has recently been published.² The physical properties of the various specimens of colour will thus shortly be available, but the matter is receiving considerable attention in America, and it is possible that the basis of graduation in such systems may still further be improved. Meanwhile the Munsell Atlas affords at least a definite and *practical* system, provided that different issues of the atlas are consistent among themselves.

In order that a clearer conception of colour variation and possible notations may be formed, we may now proceed to consider some geometrical ideas which have naturally been evolved from the three-dimensional variation of colour, to which attention has already been drawn. The object is the representation of a colour by a point in a geometrical figure.

Maxwell's Colour Triangle.—The synthetic trichromatism of colour sensations led Maxwell to the formulation of the idea of a "colour triangle", in which the fundamental hue sensations are found at the corners and diluted colours in the central parts. The amount of a hue stimulation rises from zero on the opposite *side* of the triangle to 100 per cent at the corner, and mixtures of two sensations are found along the three sides. Equal stimulation of the three hue sensations is assumed to produce white. Thus white is represented in the centre. The point M (see fig. 14) corresponds to a colour containing about 30 per cent of blue sensation,

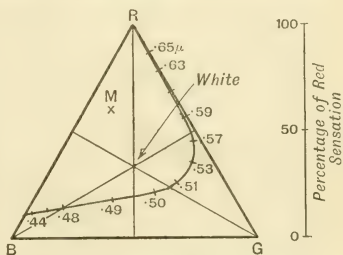


Fig. 14.—Maxwell's Colour Triangle

¹ *Atlas of the Munsell Colour System*, Munsell Color Company, 120 Tremont Street, Boston, Mass., U.S.A.

² Bureau of Standards, Washington; Technical Paper, No. 167, 1920.

60 per cent of red sensation, and 10 per cent of green sensation stimulation. It will be seen at once that the point is situated at the centre of gravity of three masses proportional to the amounts of red, green, and blue situated at the corresponding apices of the triangle.

This device represents variations of hue and saturation, but does not exhibit brightness or luminosity.

The colour triangle can be used, as is done by Bawtree and Houston, to record and express colour mixtures of light derived from three colour filters, approximately red, green, and blue-violet; the necessary condition being that the amounts of the three lights in any mixture are to be expressed on such a scale that equal quantities shall produce white. No assumptions as to the spectral purity of the components need be made, for the location of colours in the triangle will be determined solely by the special nature of the filters employed. There is, in such a case, no exact reference to the stimulation of the primary red, green, and violet sensations as conceived by the trichromatic theory. It should be noticed that variations of photometric intensity or brilliance are found on going over the triangle.

In Chapter IX the determination of the stimulation of the theoretical primary colour sensations by the hues of the spectrum will be described. From those results the spectral colours can be located in the triangle, when they are found to lie along a line which runs first almost along the side RG and then nearly parallel to the side BG, as suggested in fig. 14.

Colour Pyramids.—When it is desired to exhibit brightness, a three-dimensional figure is necessary; but although it appears simple at first sight to represent black by the apex of a downward-pointing pyramid (when increasing intensity of white light is found on rising along the central “equal stimulation” line of the pyramid) difficulties arise when it is desired to make equal luminosity appear *all over* one horizontal level, because the luminosity values of the red, green, and violet sensations are by no means equal when they can be united to form white.

Titchener's Colour Pyramid (fig. 15).—Again it is often desired by psychologists to make a figure to represent in a similar way the sensations due to the colours of material bodies, in which case the maximum of brightness is a 100-per-cent reflection (as in an ideal white). Titchener's pyramid is based on the principles of the Hering opposition theory (to be discussed in the chapter on colour vision), red and green, yellow and blue being found at

opposite corners of a four-sided pyramid, which is pointed towards *black* below and *white* above.¹ Greys are found along the central line as before, and the saturated colours on the outside of the figure. The fundamental hues at the four corners are not equal in brightness, yellow being brightest: thus a plane of equal saturation is depressed from the yellow towards the blue. Points in such a pyramid represent various colours differing in hue, in saturation, and in brilliance.

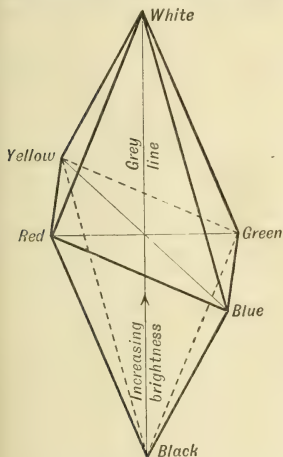


Fig. 15.—Colour Pyramid, after Titchener

Munsell's Colour System.—

Students of mathematics will see in the three-dimensional figures an attempt to picture the three possible

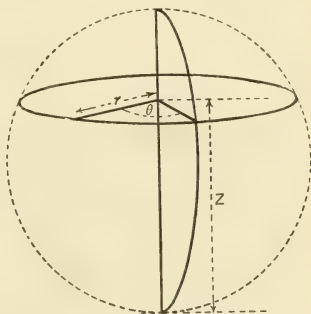


Fig. 16.—Cylindrical Co-ordinates to show Points in and around a Sphere

variants in colour in terms of Cartesian co-ordinates. The Munsell system is exhibited in a similar way by the colour sphere and colour tree, but “cylindrical” co-ordinates are now employed.

We imagine a sphere with a fixed vertical axis. Planes at right angles to the axis intersect the sphere in uniform “levels”, which are to represent definite amounts of brilliance or value. White (the highest value) is placed at the “north pole” and black at the opposite lower pole (see fig. 16). Any point in space can then be represented by three quantities, its level, its distance from the central axis, and the angle which the line in the same level joining it to the central axis makes with some fixed plane passing through the axis, just as longitude on the earth is measured with reference

¹ Hering's theory is based on the observation that in mixtures of certain reds and greens, or certain yellows and blues, hue is destroyed and white produced.

to the meridian of Greenwich. It is preferable, however, to carry the measurement of the angle quite round to 360° in one positive direction.

If this co-ordinate system is clearly understood, the method of representing a colour will be apparent when we employ the level or vertical co-ordinate (Z in fig. 16) to represent the *brilliance* or *value*, the angle θ to represent the *hue*, and the radius r to represent the *saturation* or *chroma*, which is the fraction expressing the ratio of the brightness of the pure hue sensation to the brightness of the whole sensation caused when the coloured light is received by the eye from the specimen in question, for we are dealing with the colours of material objects.

In order that greys may be found along the line joining the poles, it is evident that any hue must be exactly opposite (or 180° away from) its complementary hue. Thus in vertical planes passing through the axis all variations in value and saturation of a hue and its complementary must be found. In any horizontal plane at right angles to the axis all possible variations of hue and saturation will be experienced, but always at the same apparent brightness. It is difficult for some observers to judge the relative luminosities of differently coloured lights, but this is found to be largely a matter of a little experience. The Munsell colour photometer is an instrument designed for the comparison of values in the case of pigmented surfaces and the like; it was used in preparing the colour atlas based on the Munsell system.

The hue scale in this system is graduated from 0 to 10 in ten sections, R, YR, Y, GY, G, GB, B, PB, P, and RP, the initials having obvious meanings. The value scale is graduated in ten divisions from 0 (black) to 10 (white), and the chroma scale from 0 (grey) to 10.

The points representing the colours of actual pigments in this co-ordinate system are by no means confined to a sphere. The Munsell "colour tree" (see fig. 17)¹ has branches which reach out to points representing the spectral colours, and the actual model of the "tree" is intended for use in teaching. The possible means of determining the co-ordinates of a given colour can hardly be understood till the subject of colour-vision has been more fully discussed, but with the exercise of a little imagination it will be possible to refer colours fairly nearly to their proper places. For

¹ I am indebted to the Munsell Color Company for permission to use this diagram.

example, we might imagine a series of coloured cards representing the colours of the spectrum as nearly as possible in brightness and saturation. It will be found that the yellow possesses the maximum value, red and green will be lower and about equal, while blue and violet are lower still (see fig. 17).

For practical reasons Mr. A. H. Munsell chose as a standard of saturation a pigment, English Vermilion Deep (which measures $R \frac{4}{10}$ in his system). This pigment was chosen because it was found to possess uniform quality and considerable permanency.)

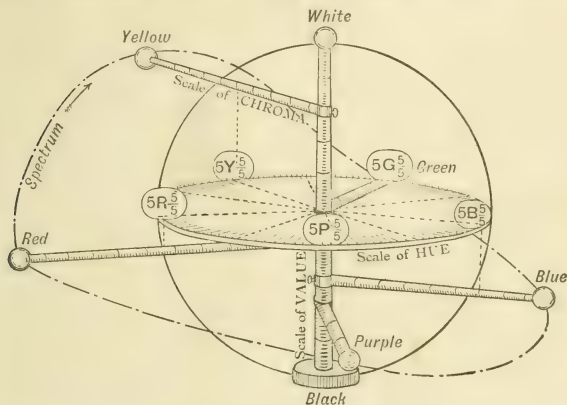


Fig. 17.—The Colour Tree

The exact chroma of all the other colours, except this $R \frac{4}{10}$, was determined by the use of Maxwell's discs. Spectral colours, fugitive pigments, and dyes may possess a saturation greater than this standard, and are expressed in relation to it as $/11$, $/12$, $/13$, or $/14$ steps from neutrality.

At differing brightness-values the varying hues will obviously be shown at differing degrees of saturation, as with the naturally "darker" colours a greater proportion of white will have to be added in order to bring them up to a required "value".

A colour might then be specified as (for example) $4 \text{ GB } \frac{3}{6}$. This would indicate a hue of green-blue (No. 4) of brightness 3, and saturation 6.

The organization of the colour atlas will now be understood. To quote the published description:

"The first three charts illustrate the three-dimensional basis of this colour system. . . .

"Charts R, Y, G, B, and P are vertical planes through the colour tree and colour sphere, and show the five respective colours, red, yellow, green, blue, and purple with their true complementaries, and are graded through the two other measurements, value and chroma.

"Charts 20, 30, 40, 50, 60, 70, and 80 show the five principal colours and the five intermediate colours of the Munsell system in their proper relation to the two other measurements, hue and chroma—each chart showing colours at one value only, starting with chart 20 (very dark) and going up to chart 80 (the lightest that can be practically made)."

The Bureau of Standards, in reporting on the colour atlas, states that the Munsell value numbers are not actually directly proportional to the brightness of the reflected light, but are proportional to the square roots of the true values. They are, however, extremely *consistent* among themselves. It is suggested that in order to obtain approximately equal steps of value, as far as *visual appearance* goes, "the reflections of the various members of the series of cards should form a geometric series; that is, the ratio of the reflections of any two adjacent cards in the series should be constant throughout the series".

This report concludes with several recommendations as to the physical specification of the colours to be used in such a colour atlas.

Nobili's Colour Scale.—One of the most interesting attempts, from the historical standpoint, to make a scale of colour with a definite physical basis is that due to Nobili. (The system makes use of the interference colours of thin films,) and the standard specimens consist of a number of steel plates brightly polished and coated with uniform silver films of graded thicknesses, which thus show the well-known succession of interference colours. These were classified by Newton in the following order, starting from the film of least thickness.

1. Black, blue, white, yellow, red;
2. Violet, blue, green, yellow, red;
3. Purple, blue, green, yellow, red;
4. Green, red;
5. Greenish blue, red,
6. Greenish blue, pale red;
7. Greenish blue, reddish white.

Although there might thus appear to be a repetition of colours, this is not the case, as the saturation undergoes constant changes between the above sections, and there is thus a very considerable colour range.

Nobili's scale covers the colours in sections 1 to 4 in the above list (approximately). The forty-four plates are at present exhibited in the Museo di Fisica at Florence, and even to this day the colours retain a fair brilliance. The system will, however, be found hardly practical for modern requirements, although it might be of value in the "colour" method of controlling the tempering of steel.

Practical Methods of Colour Measurement.—There seems to be little doubt that a good colour atlas, well made and duly tested, is the most simple means of identifying and classifying a colour, provided that no great accuracy is required. The main objection to the use of the atlas will be the possible changing of the colours with the lapse of time, but storing in darkness and prevention of dampness will satisfactorily keep such a chart constant for many years, especially if the use of unstable pigments is avoided.

There may, however, be cases in which more accurate and definite results are required, and in this case it is necessary to employ one of the forms of colour-measuring *instruments* which have now been developed.

It is not the intention to do more than classify these instruments at present. Their description must be reserved for a later chapter.

Firstly, it may be stated that spectrophotometers are instruments which really measure definite physical characteristics of substances, whereas colorimeters measure only the appearances. A spectrophotometric analysis gives complete information as to the transmission or reflection coefficients of a body with regard to any part of the visible spectrum. From such information, with a knowledge of the facts of colour vision, it is possible to predict (although with considerable trouble) the appearance of the body under definite conditions of illumination—but the converse is not true, i.e. the physical properties of the substance cannot be predicted accurately from a measurement concerning its appearance.

The Colour-patch Apparatus (see p. 96) is essentially a research apparatus, as it requires a specially darkened room for its successful use. In the forthcoming chapters its use for colorimetric analysis and also for spectrophotometry will be described. It would, perhaps, be hardly advisable to install it for ordinary commercial measurements, unless anything in the nature of serious investiga-

tion is to be undertaken, although it is unquestionably most convenient for measuring the *reflection* coefficients of opaque substances.

Spectrophotometers.—These instruments are highly convenient for measuring the transmission coefficients of glass, dyes, and the like. Quite a number of types are extant, including the König-Martens, Nutting, and Glazebrook forms, the two first mentioned being the more suitable for work of the highest accuracy. As was previously mentioned, the König-Martens instrument (by means of the use of an “integrating cylinder”) may be employed for the measurement of reflection coefficients. The method will be more fully described in Chapter VIII.

Colorimeters.—These instruments (intended, as the name implies, for the measurement of colour) may be divided into four classes. The first class measures a colour directly in terms of hue, saturation, and brightness. This is accomplished by the colour-patch apparatus or by the Nutting colorimeter.

The second class employs a three-colour synthesis to match the unknown, the primaries being, in general, arbitrary. Calculation is needed in this and all following classes to reduce the results to terms of hue, saturation, and brightness. Examples are the Bawtree colorimeter and the Ives colorimeter. The colour-patch apparatus may also be used in this manner.

The third class employs the subtractive process of colour mixing, but a range of depths of the subtractive primaries is necessary. This is given in a number of separate glass slips in the Tintometer method, or by means of “wedges” in the Jones colorimeter.

The fourth class comprises one instrument only, which is unique in producing its colour matches by polarization methods. This is known as the Arons colorimeter.

This completes the list of the better-known colorimeters. There remains the limited-range colorimeter (Duboscq and other types); instruments of this kind are simply for estimating the amounts of definite impurities, or the concentration of liquids and solutions, or, in other words, colour variations along one definite path only in the colour continuum. There is no attempt to measure hue, saturation, or brightness as such.

Fuller descriptions of all these instruments are given in Chapter VIII.

CHAPTER IV

Colour in Regard to Illumination

Natural and Artificial Light.—Emphasis has been laid in previous chapters on the subjective nature of many colour phenomena. If the surroundings of the eyes are entirely illuminated by light of a specific hue, the sensation of the depth of the hue undergoes a gradual change in the direction of apparently diminishing saturation. Thus it is that the wide variations in the colour of daylight very largely escape notice, and even the more drastic changes in passing from daylight to artificial light are not appreciated unless in some accidental way they are brought into prominence by an effect of simultaneous contrast.

This may be realized in a striking manner by an experiment such as the following: In a room not too brightly illuminated by daylight from a north window a strong artificial light is used. It is then possible to obtain (on a white surface) two shadows of an object such as a pencil, illuminated one by daylight and the other by light from the artificial source. The contrast as seen in the shadows between the colours of the lights is then very marked, one generally appearing a deep blue, while the other is a brown. Such contrasts between the colours of the lights from various sources are familiar to those who have done photometric work, and are seen especially well in a photometric matching field such as that of the Lummer-Brodhun "head". (See p. 103.)

Such effects, however, are always appearing in nature. It has been said that one of the great features of modern art is its careful study of shadows, and truly the contrasts between blue shadows, illuminated by light from the blue sky, and sunlight, so often seen on snow, are extremely beautiful, especially when a little haze in the air makes the sunlight more golden than usual. Any artist should be doubly armed in this matter who can supplement his observation by a knowledge of the properties of light and his own visual processes.

These differences in the colour of lights which would give a continuous spectrum are entirely due to the differences of relative energy distribution between the various wave-lengths. Any considerable increase of energy in a particular spectral region means a change in the colour of the light.

Students of physical optics will be interested in the discussion of the nature of white light. Although there is no difficulty in explaining most of the phenomena of dispersion on the supposition that white light is the product of arbitrary pulses, yet the facts of energy distribution in the spectrum point to the necessary existence of some great regularity in the disturbances, which we call light waves, arising from bodies at definite temperatures.¹

Radiating Bodies.—Inasmuch as light is always derived from some radiating substance, and most often by reason of the high temperature of the radiating body, the study of the connection between temperature and radiation is of great importance. The effects of reflection, transmission, and absorption which may occur when light falls on a material substance have already been described; it must now be stated that the absorption of radiation is accompanied by a rise in the temperature of the absorbing body. When the temperature of the body becomes higher than the temperature of its surroundings, it begins to radiate more energy than it receives in the same way, and thus tends to fall in temperature. This radiation derived from the substance must be carefully distinguished from any energy reflected from it. It is found that (under the same conditions) various substances differ considerably in the rate at which they radiate energy to bodies at lower temperatures. Those which absorb radiation most completely are found to be the best radiators; thus a black substance like charcoal (which is black because it reflects very little light and absorbs a large proportion of the radiations falling upon it) is found to radiate well when its temperature is raised. The conception of a perfect radiator, which is also a perfect “black body” because it would absorb all radiation and reflect none, is thus easy to form. The mouth of a cylinder, bored in charcoal or carbon and closed at one end, approaches very nearly in its performance to the ideal radiator.

The radiations caused by a rise in temperature of such a “black body” can be submitted to analysis by suitable dispersing systems similar to the spectroscopic apparatus previously described, but having prisms and lenses of rock-salt or mirrors in place of lenses.

¹ Schuster, *Phil. Mag.*, June, 1894.

It is found that the characteristics of the radiation depend solely on the temperature of the radiating body, and not at all on the wave-lengths or other characteristics of the radiation which may have been previously absorbed.

Lummer and Kurlbaum's Experiments.—Lummer and Kurlbaum have studied the distribution of energy in the spectrum of a hot "black body" or perfect radiator, by means of a delicate electrical thermometer (which can be moved about in the plane of the spectrum) called a bolometer. The heating effect at any point is a measure of the energy corresponding to the particular short range of wave-length falling on the instrument. Fig. 18 shows the distribution of energy corresponding to certain temperatures. As the temperature increases the energy is crowded more and more into the shorter wave-lengths. In studying the figure it should be remembered that the visible spectrum is confined to a very short range (0.4μ to 0.7μ) on the left of the figure. Note the increase in the total energy and the shift of the maximum ordinate to shorter wave-lengths as the temperature rises.

Spectral Distribution of the Energy of Light Sources.—Although in some cases artificial light

sources do not act entirely like perfect radiators, yet the similarity is sufficiently close to enable an estimation of the differences in radiation to be made. Table 6 in the Appendix, p. 180, gives approximately the temperature of certain light sources, and fig. 19 shows graphically the differences in the spectral distribution of energy based on figures obtained at the Nela research laboratory. It should be noted that, in order that light of *approximately* the same visual brightness may be compared, the ordinates for the curves have been reduced to the same value for wave-length $\lambda = .589\mu$.

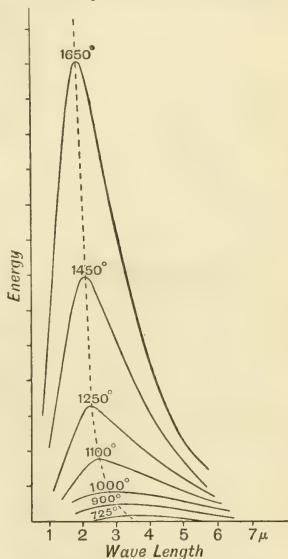


Fig. 18.—Energy and Wave-length

Daylight and its Variation.— The light from the sun corresponds to the radiation from a "black body" at a temperature of about 5000° C. At present this temperature cannot be reached in any practical illuminant. Sunlight is often very considerably modified in its passage through the atmosphere, but least when it passes through the minimum thickness of clear dry air to the earth's surface, e.g. on a clear day at noon when the sun is high

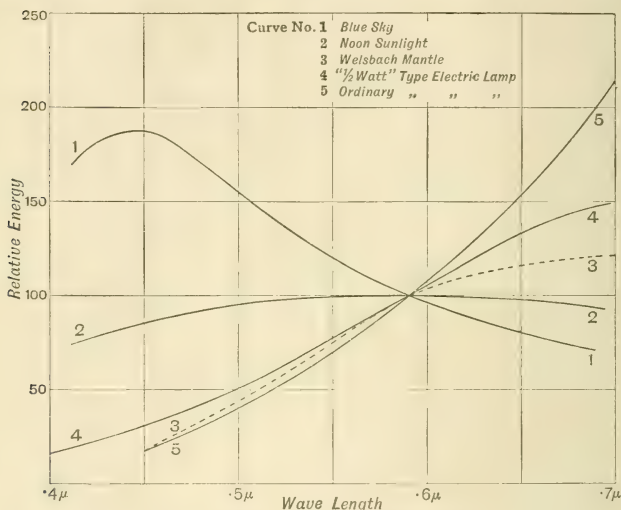


Fig. 19.—Energy in Spectrum of various Sources

in the heavens. If any haze is present, a great deal of scattering takes place, mostly in the shorter wave-lengths, and the light becomes increasingly yellow and red. The light from blue sky is all scattered light, and recent work by Lord Rayleigh tends towards the conclusion that the blue light is due to the molecules of the air and not to dust particles, &c., as was originally supposed. It is an interesting fact that although the sun must be radiating a great deal of energy as ultra-violet light, no waves shorter than $\lambda = 0.29 \mu$ reach the earth's surface, and the ultra-violet waves left in the spectrum between this point and the visible limit have their intensity greatly reduced. The theoretical explanation of this fact is

that a layer of ozone in the upper atmosphere absorbs this light, which undoubtedly would be extremely injurious to our eyes.

The extreme variations in daylight can hardly be appreciated from the curves, as the range between white sunlight and blue sky is only half the story. The variations in sunlight, as has already been hinted, are very great and profoundly modify its actinic power, a fact which has been the despair of many amateur photographers when, for instance, the shorter and more chemically active wave-lengths are missing in the bright light from the setting sun.

Then we have to consider the variations due to clouds and fog. There will also be considerable variations due to the surroundings of a locality. Objects outside the window of a room will often cause tremendous variations in the quality of the incoming light.

One of the most thorough investigations in this subject has been carried out by Nichols¹, who conducted spectrophotometric measurements on daylight, using an acetylene flame as a comparison standard. This is one of the "whitest" of artificial sources, and, although the relative differences in intensity throughout its spectrum as compared with sunlight must have been generally very large, a fairly consistent and portable standard was thus secured.

Nichols conducted many experiments both in America and in Europe. His results, though not given directly in terms of energy distribution, may readily be used for computing this from the energy-distribution curve for blue sky given here. The investigations included light from overcast skies, and Nichols found the light from some of these to differ little from the light from some blue skies.

It will be realized that the term "daylight" covers a multitude of varieties of light, and that even "white light" needs specification in critical measurements.

Characteristics of Artificial Lights.—Artificial light, as has been shown, is generally very yellow in comparison with any daylight, except that from the setting sun, but artificial illuminants have great ranges of energy-distribution amongst themselves. It is interesting to compare the curve (see fig. 19) for "incandescent" gas light with that for an electric lamp. Amongst electric lamps we have the carbon filament with the most yellow light of all, the ordinary straight-metal filament type with a whiter light, then the "half-watt" lamps, in which the metal filament is coiled and heated in an atmosphere of nitrogen or argon. The half-watt lamps differ in quality of light amongst themselves, the lower "wattages" being

¹ Nichols, *Phys. Rev.*, Vols. XXVI and XXVIII.

relatively less efficient, both as regards light and whiteness of light, than those taking greater power. Then come the new vacuum tungsten arc lamps, in which efficiency and temperature can be pushed still higher. The crater of the carbon arc gives a very white light in comparison with most artificial lamps, but the violet radiations from the flame of the arc are sometimes prominent. Also the temperature is liable to changes owing to variations in the current, imperfections in the carbons, &c.

Incandescent gas light was mentioned above. Although a very high temperature is not reached, the "rare earths" or oxides, from which the mantle is made, depart very much from the properties of a black body. By varying the composition of the mantle the light may be given a greenish or bluish tendency. No doubt, as far as an uncorrected lighting unit goes, the light is one of the nearest approaches to daylight which can be obtained. The tremendously greater relative intensity of the yellow and red regions in the spectra of artificial illuminants, as compared with daylight, is the main thing to bear in mind.

Effects of Variations in Light on the Colour of Objects.

—In the case of light filters, or of objects which transmit or reflect a single narrow range of wave-length in the spectrum, no great alteration in colour can be expected through altering the colour of the illuminant, although the apparent brightness of the object may be considerably affected. We can, however, consider an object which reflects red and blue light simultaneously, as, for instance, a purple fabric. Light from a north window may give rise to a reflected light, which contains red and blue in the proportion of one to two, but if we use the light from a half-watt lamp the proportions may easily become three to one. In the first case we should have a fairly bluish purple; in the second case it would appear decidedly red.

There are similar changes in the "warmth" of colours in passing from sunlight to blue-sky light, although these most frequently escape observation owing, doubtless, to the great simultaneous change of brightness which renders the observation of the simple hue change rather difficult. The most violent colour changes of this kind are always found in colours which are formed by the union of two or three parts of the spectrum, especially when there is a sudden increase in reflecting or transmitting power in the extreme red. The red light reflected will not be relatively important in daylight perhaps, but in artificial light it is likely to start into

tremendous importance and profoundly modify the appearance of the object. Fig. 20 will illustrate this point. It shows the spectral reflection, as found by the colour-patch apparatus, of two fabrics kindly supplied by Messrs. Eastman, Ltd.

- (1) is dyed with benzyl violet 5 BN and quinoline yellow, and in blue-sky light it is of a moss-green colour, but in artificial light it becomes quite brown.
- (2) is dyed with benzyl violet 5 BN, formyl violet 10 B, and quinoline yellow. In blue-sky light it matches very well with a dark navy blue, but in artificial light it becomes quite a dull red in colour.

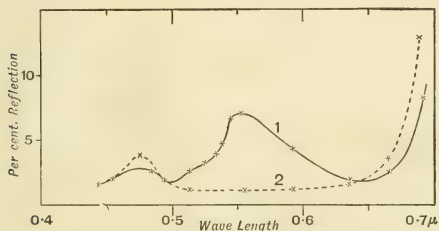


Fig. 20.—Showing Spectral Reflection of two Special Fabrics (1) and (2)

The fabrics exhibit a kind of intermediate effect in summer sunlight.

There is a very interesting effect which can easily be noticed with these so-called sensitive tints. As was pointed out in the chapter on vision, the retina is pigmented with a yellow colouring matter at the macula lutea, perhaps in order to cut down any blue or violet haze which we might otherwise see owing to the non-achromatism of the eye. This yellow pigment acts in daylight in the direction of the reduction of the relative intensity of the short wave-lengths, and this produces a kind of local artificial light effect which appears as a region of modified colour, moving about wherever the direction of the eye is turned when looking at the fabric.

Colour changes are not usually so marked as in the two cases described, but as they are still present to a greater or less extent with all coloured objects, the necessity of working in artificial light in any connection where exact colour is of importance is a serious disadvantage, but we shall shortly understand how this difficulty may be overcome.

Artificial Modifications in the Colour of Light.—Little need be said as to the modifications in the colour of light which are produced by means of coloured shades, reflectors, &c., in domestic lighting. The probable effect of such will easily be estimated in the light of the simple methods of colour analysis which have been explained in previous chapters. It should be remembered that modification in the direction of red or orange, although producing an appearance of greater warmth, will probably minimize the effect of any scheme of colour decoration. The effect of pictures will be almost entirely spoilt. For many purposes, however, a pink or yellow shade, of which the colour will shine out brilliantly with artificial light, may be very suitable.

The importance of the colour of the light where the best effects on interior decoration are required has no better example than that given by the cathedral of S. Marco, Venice, where the windows are of colourless glass in order that the beauty of the interior marbles and mosaics may not be lost.

The colours of objects outside the window and the walls of the room produce modifications in the daylight admitted which should not be forgotten. In places where good lighting is essential, the importance of having pale colours for the decoration of walls is very great, as a good white reflecting surface will return more than 80 per cent of the light incident upon it. Although white will not often be chosen, yet the saving of even 20 to 40 per cent of the light falling on the walls is a consideration in days of expensive lighting.

Artificial Daylight.—The possibility of modifying the distribution of energy in the spectrum of an artificial source by a suitable light filter suggested the possibility of correcting light to daylight quality in this way. In 1892¹ A. P. Trotter suggested "that a glass or other medium may be tinted with stains or dyes which will absorb the proper amount of yellow and red light, . . . or a reflecting screen may be painted with such a colour that this yellow light may be absorbed and the white light alone may be reflected".

Dufton and Gardner brought this suggestion to a practical issue by a lamp patented in 1899 in which a glass filter, coloured blue-green by means of copper and a trace of uranium, is used to correct the light of an enclosed electric arc lamp. It is stated that the "excess of violet" is corrected in this way.

In 1910 Kenneth Mees produced a compound screen of two

¹ *Jour. Inst. Elect. Eng.*, Vol. XXI.

glasses and a dyed gelatine film for the correction of ordinary metal filament electric lamps, and about this time Mark Barr also produced an arrangement of filters and reflecting screens for illuminating a studio by artificial daylight.

Ives and Luckiesh in 1911 proposed the combination of a light green glass with a cobalt glass, and a gelatine screen dyed with an aniline dye to neutralize the green part of the spectrum of the cobalt glass.

In general, however, the dyed gelatine screens seem to have been found wanting in practice, possibly through lack of permanency.

In 1914 Ives and Brady produced a glass for accurate colour matching with the Welsbach lamp and the tungsten gas-filled lamp, and a glass is now available for the satisfactory correction of half-watt type electric lamps, due to Dr. Gaze of America. These glasses are of a lead potash basis with various proportions of cobalt, manganese, nickel, and copper. For making filters it is used in blown or pressed sheets averaging 6 mm. in thickness. Messrs. Chance Brothers, of Birmingham, have now produced a similar glass.

The use of filters, as would appear from the words of Mr. Trotter quoted above, by no means exhausts the possibility of correction. In 1918 Mr. G. Sheringham, an artist, made use of a double-tinted reflector with a metal filament lamp so constructed as to throw much of its light on the reflector. This latter was covered by washes of about equal areas of green ink and violet pigment, and it was found that the quality of the light for painting was immensely improved. The present writer, in collaboration with Major Klein (working from this suggestion), devised a lamp in which all the light is corrected (and diffused at the same time) by reflection at the surface of the reflector mainly covered with small areas of green and blue pigments.

Possible Efficiency.—The problem both for the case of filters and reflectors may be considered by reference to fig. 21, in which the curves for energy distribution of the gas-filled lamp, sunlight, and blue-sky light are reduced to the same ordinate at 0.45μ .

In order satisfactorily to correct the gas-filled lamp it would be desirable to devise a filter or reflector which, while transmitting or reflecting 100 per cent as nearly as possible for the short wave-lengths at the end of the visible spectrum, should give increasing absorption (corresponding to the elimination of the whole of the shaded portion of the figure) if it is desired to reproduce blue-sky light.

The violet in the spectrum is of very low visual intensity, so that if the correction starts at 0.45μ it will be sufficiently good. Under these circumstances it can quite easily be found (from the diagram, by the help, if necessary, of the table of spectrum luminosities given elsewhere) that to correct the light to sunlight we must sacrifice 67 per cent of the light, while for correction to blue-sky light we must sacrifice 81 per cent.¹

These figures refer to the case of a high-efficiency gas-filled lamp working at 22 lumens per watt. With lamps of lower efficiency even the above figures cannot be attained.

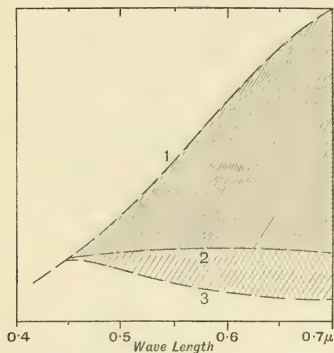


Fig. 21.—Energy Distribution Loss in Correction

Correction by Filters and Reflectors.—Naturally it is not usually convenient to have a filter as the lamp bulb (it is expensive, and the correction may not be very accurate); also it is not possible to obtain 100 per cent transmission at 0.45μ with a filter or reflector of the necessary depth of colour. Further, the light has to be furnished with a reflector unless the correcting glass is blown as a lamp bulb. Thus, in the commercial filter units (blue-sky type of correction) which give a

localized illumination (such as for a table or counter), the overall working efficiency, as compared with that of the naked lamp, is not more than 14 or 15 per cent. With ordinary tungsten lamps the efficiency is even lower, of the order of 5 to 10 per cent. Using the *reflector* method with gas-filled lamps, the overall efficiency in the commercial models is said to be little lower than that of transmission units which give the same type of correction. Values of efficiency higher than those quoted above are given by certain types of unit at the expense of the quality of the light.

The reflector models fulfil several important requirements, among

¹ These figures are largely based on results of the Nela laboratory quoted in Luckiesh's *Color*. Makers of artificial daylight units should now give definite information as to the type of energy curve produced by, and the overall efficiency of, their units.

these being the diffuse nature of the light, the possibility of illuminating large areas with a single powerful lamp, and the obviation of the necessity for the entire enclosure of the bulb. The rationale of the method of correction¹ is set forth in a paper by the present writer published in the *Illuminating Engineer*, Feb., 1920. Having given the figures for the energy distribution in the spectrum of the watt lamp and the percentage reflection coefficients of a pigment, we can calculate at once the relative distribution of energy in the light reflected from unit area of that pigment. If we wish to combine the light reflected from unit areas of two pigments, we find the energy of the combined light by adding the corresponding figures for the two. This corresponds to the case where a reflector is entirely covered with an equal number of small areas of both pigments. We can proceed in a similar manner for any number of pigments present in definite proportions of area. In the following table the energy distribution from a reflector, having equal areas of emerald green and ultramarine with one-tenth the area of vermilion, is shown. In such a manner it is easy to obtain any required type of correction quite definitely.

RELATIVE DISTRIBUTION OF ENERGY IN REFLECTED LIGHT FROM
HALF-WATT-TYPE LAMPS

	Emerald Green.	Ultramarine.	E.G. + Um.	$\frac{\text{Vermilion}}{10}$	E.G. + Um. + $\frac{V}{10}$
$\cdot 692 \mu$	9.5	5.97	15.47	10.4	25.87
$\cdot 638 \mu$	11.3	3.65	14.95	12.6	27.55
$\cdot 589 \mu$	18.7	2.67	21.37	7.9	29.27
$\cdot 555 \mu$	29.6	2.25	31.85	1.6	33.45
$\cdot 490 \mu$	25.0	7.3	32.3	0.4	32.7
$\cdot 457 \mu$	7.4	15.7	23.1	0.3	23.4
$\cdot 427 \mu$	1.9	9.8	11.7	0.2	11.9

It is seen in the case given above that in seeking to obtain a sunlight correction considerable advantage is obtained by introducing a little vermilion into the reflector. This is also the case in other states of correction. In fig. 22 curve 3 represents sunlight, curve 1 a correction with emerald green and ultramarine, and curve 2 the improvement introduced by vermilion. A satisfactory approach

¹ In the commercial forms of the lamp the correction has been considerably improved by the use of better pigments than could be obtained for making the earlier experimental models.

to blue-sky light may be made by increasing the relative amount of ultramarine. In fig. 23 curve 2 represents the blue-sky light, and curve 1 the artificial light corrected almost to blue-sky quality.

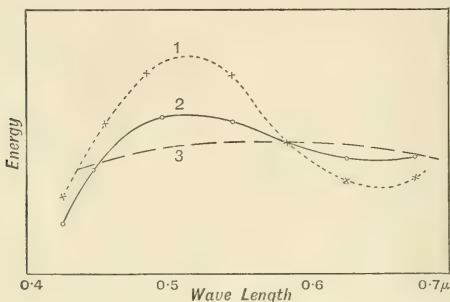


Fig. 22.—Correction by Vermilion

If exact correction is required, the efficiencies of practical units of any type for sunlight effects may be inferred from the relation of practical attainment to the "maximum possible" in the case of blue-sky units. The ideal efficiency of 33 per cent will not be

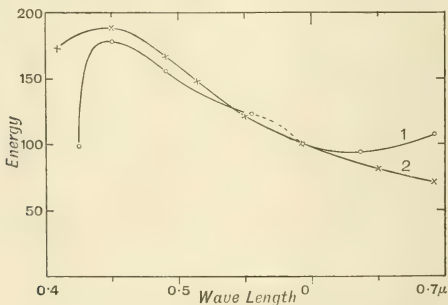


Fig. 23.—An Attempt at Blue-sky Energy Distribution

attained, but something like 25 per cent may be realized. Naturally if a less drastic correction is required, the efficiency may be very much increased, while an improvement in the quality of light sufficient for many purposes is still given. Lamps of this kind are available with bulbs of blue-green glass giving an efficiency

of 60 per cent, but the quality of the light does not nearly approach even that of sunlight.

In considering the necessary type of artificial daylight required for certain purposes, there are a good many factors to be remembered.

Firstly, dye-works and other colour-matching industries will need both types, i.e. sunlight and blue-sky units, because colour changes between sky light and sunlight may be important. Artists, too, will probably prefer blue-sky units, as sunlight gives too great a "warmth" to a picture; but it should be remembered that a picture will not always be viewed by blue-sky light, nor is the studio north window always receiving such light. Probably an intermediate correction would be most satisfactory. Drapers' shops again need

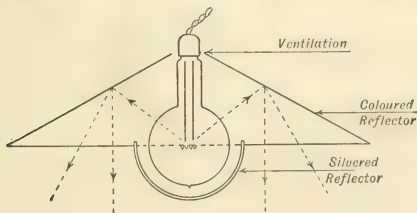


Fig. 24.—Diagram of Sheringham Daylight Lamp

a unit which gives a kind of average daylight. Any unit which professes to copy daylight will be submitted to very free criticism and testing. If colour changes are found between the lamp light and daylight, confidence will be shaken. Therefore an *approach* to sunlight is of little use except where a mere improvement in the colour-rendering powers of the light is needed, such as for florists, shop windows, lighting in private houses, &c. Entirely new stage effects will be attained with artificial daylight, but it will place more severe requirements on the excellence of the scenery.

Luckiesh states that about 15,000 "north-sky light" units are in operation in America at the present time, as well as others giving sunlight effects. The more general use of such daylight lamps in Great Britain could not fail to result in a great saving of time in bad weather, and would thus give an impetus to many industries. Furthermore, since efficient and permanent artificial daylight units are now available, there seems every reason for opening our picture galleries at night, and thus making them accessible to the workers who have no opportunity to visit them during the daytime.

Fig. 24 shows a reflecting type (Sheringham Daylight), and fig. 25 a typical transmission type, artificial daylight lamp.

Coloured Light for "Magical" Stage Effects.—If a design is painted on white paper with a wash of some light red pigment, the pattern becomes practically invisible when illuminated by spectrally pure red light, but stands out strongly when illuminated by blue-green light.

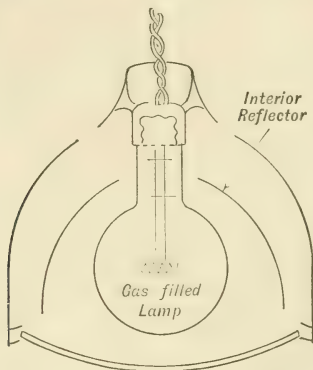


Fig. 25.—Typical Transmission Daylight Lamp

It will be realized that there are many ways in which similar effect can be used for the variation of scenic effects on the stage in connection with suitably painted backgrounds. A painted "window" in a wall could be made to disappear, ghostly figures may appear and vanish; a thousand and one possibilities present themselves.

In this connection, too, the possibility of using the sensitive tint materials for queer variations of colour in clothing might be remembered.

CHAPTER V

Colour in Human Experience

The Development of the Use and Study of Colour.—

Certain evidence points to the probability that sight and colour vision are the results of long processes of biological evolution. Apart from any other consideration, the power of distinguishing colours was, and still is, a tremendous advantage in aiding the rapid visual perception of objects so important in savage life for defensive and protective purposes. The beginning of the æsthetic appreciation of the colours and forms of nature is naturally lost in obscurity, but in very early times images and idols were crudely smeared with rough colour in imitation of life.

The Ancient Egyptians and also the Assyrians and Babylonians practised tempera painting, but with little idea of the exact imitation of nature. Dark outlines were filled with flat colours from an extremely limited palette comprising perhaps charcoal, chalk, the red earths, ochre, vegetable yellow, and blue from crushed blue glass. The Greeks had a wider range of colours, for Tyrian purple and Egyptian blue must have been known to them, and their statuary is believed to have been painted in strong colours. Greek painting, however, seems not to have reached a level of technical excellence equivalent to that attained by the sculpture of that period.

In Roman times the range of pigments had increased to a satisfactory selection.

Although the art of fresco painting (or painting on wet plaster) was known very early, being used chiefly for the interior decoration of buildings, it was not until the time of Van Eyck (born A.D. 1390) that oil painting was introduced. The possibility, with this method, of any amount of alteration and correction has brought it to the fore, water-colour painting being a valuable secondary process.

The study and appreciation of colour has been intimately bound up with the development of art, but in recent years students of experimental psychology have approached the subject of colour in

the thought of humanity from a more introspective standpoint.

Colour Preferences.—In this connection definite results have been obtained, but the significance of these is somewhat difficult to gauge. However, it appears that definite data¹ of some consistency have been given by Bradford, Cohn, Winch, Titchener, Luckiesh, and others. Luckiesh, for example, describes a series of experiments in which coloured papers of fairly well saturated hues were used. The subjects were asked to place them in order of preference. The general results indicate a preference for purples, red, and blue, green being somewhat lower in preference, and yellow last of all.

Cohn's tests included the choice between saturated and unsaturated colours, and decisive evidence points to the preference of the fully saturated specimens. Is there a connection here between the indifference to yellow, the "nearest" colour to white, and the less saturated colours? These preferences will lead to interesting speculations as to their origin. Do we not prefer the fugitive and bright colours of the flowers to the more lasting green of the leaves? Is not red the colour of animal life, of the warmth-giving fire, and the hot blood which rises in anger; is not blue the colour of peaceful sky and sea, and the colour of many flowers?

A wider topic, and one of engrossing interest to the decorative artist, is that of preference in colour contrasts. Here again we shall most probably find that experience and association count for much, but the subject is one on which few would care to dogmatize.

Very often contrasts between degraded crimson and degraded vermilion, orange, or yellow are deemed unpleasant, and very often colours having hues found near each other in the spectrum, such as yellowish green and blue-green, are said to "clash". Nevertheless it is true that contrasts which would not be used in dress, dark green and pink for example, may be considered very beautiful in a flower garden. This seems to suggest that the emotional effect depends largely on circumstances exterior to the mere contrast, and is, to a larger extent than generally believed, a matter of convention.

Colour Harmony.—The analogy of *hue* in colour to *tone* in sound has led inquiring minds to seek for melody and harmony in colour. It is not wise to assume that such effects *must* be found, in

¹ E. J. G. Bradford, "On the Relation and Æsthetic Value of the Perceptive Types in Colour Appreciation", *Amer. Jour. Psych.* (1913), 24, p. 245; J. Cohn, "Gefühlsinn und Sättigung der Farben", *Phil. Stud.* (1900), 15, p. 279; J. Winch, "Colour Preferences of School Children", *Brit. Jour. Psych.* (1909), 3, p. 43; E. B. Titchener, *Experimental Psychology*, New York (1910), p. 149; Luckiesh, *Color Psychology*, New York (1916).

view of the vastly greater frequency of the vibrations of light and the differences in the nature of the apparatus of perception in ear and eye.

Harmony in sound is appreciated as a difference in "quality" of a dominant note introduced by the presence of another tone bearing some simple relation in frequency to the first. It is true that when lights of two hues fall on the same portion of the retina a difference of quality is perceived, but the term "colour harmony" is generally taken as applying to the relations of colours received in separate patches (although simultaneously) on the retina. Therefore it is by no means self-evident that simple frequency relations should have any bearing on this matter.

Nevertheless it is a perfectly general experience that the enjoyment of colour is enhanced by the presence of suitably chosen contrasts. In some textbooks on art it is said that complementary hues will so balance each other, but that the amounts, values, and distribution of the hues are matters concerning which no formula is desirable or available.

It is not within the scope of this book to enter into discussions of æsthetic values in colour contrasts, as can be found in books by several writers, notably by Chevreul and W. Cave Thomas. Chevreul classifies the ways in which harmony may arise (contrast, succession, &c.) and treats the subject at great length. Thomas suggests that two harmonizing hues should conform agreeably to the hues of each other's negative after-images in order to produce an agreeable nervous sensation. No doubt most persons have decided opinions, but, as was said above, it is doubtful how much of these is really fundamental to human thought.

In what manner is colour harmony appreciated? The eyes gaze at some particular object, or wander at will so that colour after colour falls in succession on the "fovea".¹ The contrasts and "colour melody" found in viewing a picture, a landscape, or a room in this manner make true "colour music".

The Venetian artists achieved their triumph of colour harmony long before theories of complementary colours were advanced or books written on the subject. Those who feel inclined to dogmatize on such matters would do well to visit the Accademia di Belli Arti, Venice, and look well at Palma il Vecchio's "Santa Famiglia". It would be difficult to explain on any formal theory the glory of the robes in the picture, blue, green, and orange, and the way in which

¹ The seat of distinct vision in the retina.

their richness serves only to render more ethereally beautiful the delicate colouring of the face of the Holy Child.

Colour Music.—A complete octave in hue frequencies is not available to human vision, but Rimington has gone so far as to construct a colour organ by means of which hues, corresponding to the possible tones and semitones of the diatonic scale, may be thrown upon a screen by the operation of a keyboard which controls shutters in a spectrum apparatus. "Music" has been written for the instrument, but it is impossible at present to say whether such an art will endure. It must be remembered (as was previously said) that colour music is always available in nature in a way that the music of sound never can be.

Protective Colouring and "Camouflage".¹—The main object in protective colouring is to mask or obscure the true form of an object. In Nature, certain animals, insects, &c., take on the colour of their usual surroundings, and to some extent the more usual effects of shadows may tend to be masked, as for example, in certain cases by the presence of lighter fur on the under part of the body.

Although it may be comparatively easy to mask an object in a definite condition of light and in definite surroundings, it is very difficult to secure this for varying conditions of illumination and environment.

Captain Howells says that "it was soon found that the only method of painting (for effective camouflage) was the 'disruptive' style". This is to paint the object in a somewhat startling although simple manner. The "pattern" has to be large, simple, and definite in relation to the object itself, and the main purpose is, by providing one or two misleading lines of violent contrast, to render the actual outlines of the object relatively much less prominent. Some big patches of white or grey on a black ship may cause it to appear to be two small ships, one towing the other, or even to appear to have the stern at the end which is really the bow. The earlier practice of painting guns, &c., with smallish patches of dull flat colours was in reality of very little use.

Colour and Health.—In this connection it will hardly be possible to do more than indicate the lines along which thought and experience are progressing. It is true that well-chosen colourings in dress and surroundings add greatly to the pleasure of life, and doubtless have their subtle effect on the health and spirits of

¹ "The Art of Camouflage", W. A. Howells, *Illuminating Engineer*, Jan., 1920.

cultured persons. The possibility of the use of colour as a therapeutic agent has been explored to some extent during the late War, in connection with the treatment of shell-shock and neurasthenia. Mr. Kemp-Prossor has an article¹ on this subject, in which the work is described. Briefly—the *suggestive* effect of colours is considered in prescribing for any requirement. Thus, colours such as “primrose yellow”, “firmament blue”, “spring green”, “apple-blossom pink”, are suggested as suitable for neurasthenia, because they suggest “Spring, the time of life and recuperation”. The subjects of colour medicine, colour and child welfare, and the like, are discussed in the same book. Mr. Kemp-Prossor states that working efficiency can be increased by surroundings of sunlight yellow.

Against the positive statements of beneficial results from methods of this kind must be placed the experience of Dr. Pressey of The Harvard Psychological Laboratory, who has conducted an extensive series of tests which seem to indicate a complete absence of colour effects (when considered as isolated factors of experience) on mental efficiency. These tests included rates of finger tapping, pressure of the hand, memorizing of nonsense syllables, free association tests, and continuous choice reactions. Such tests are well known to students of psychology, and details may be obtained from any good textbook. The tests were conducted while the subject was influenced by a wide field of definite colour, as when sitting at a large table with a white surface illuminated by coloured light. In no cases were concordant results detected. It was to be expected, perhaps, that crude tests of this nature might fail, but Pressey went further and conducted series of tests in which the subjects furnished introspective reports. Even these failed to give concordant results.

Thus it appears that such emotional and definite effects as do exist must be to a great extent personal, and are controlled very largely by experience, suggestion, and association; nevertheless, the way lies open for further work along these lines.

Visual Fatigue.—The effects of visual fatigue are important in monochromatic vision as well as in colour vision. A few simple experiments which can be performed without apparatus will illustrate some of the main points of the subject. Let the eyes look steadily for a quarter of a minute or so at some dark objects seen against a

¹ *Colour and Health: a symposium* (Cope & Fenwick, London). This book, while containing many interesting and stimulating suggestions in regard to colour, must not be taken seriously in some of its references to physics or the properties of light.

very bright sky. If, then, the direction of gaze is suddenly shifted to another part of the sky, the shape of the darker objects will be seen brighter than the surrounding sky. This *negative after image* is due to the *fatigue* of the parts of the retina which were not previously protected by the images of the dark objects. If the eyes be closed and shaded by the hands, a bright *positive after image* of the field of view will be seen.

The effects of fatigue should be well understood by artists. When the eye views the outline of a hill against a bright sky, the centre of vision will constantly shift over a small range on each side of the actual outline. The effects of fatigue will make the sky appear brighter in the immediate neighbourhood of the hill and, conversely, the hill will appear darker. As no artist can hope to reproduce accurately the relative luminosities of hill and sky in a picture, owing to the physical limitations of pigments which cannot reproduce the self-luminous effects of the sky, he may yet imitate this accentuation of contrast and so produce a more natural effect. Where the gradation between light and dark is gradual the effect is not so much noticed, as the fatigue has more time to disappear while the direction of gaze shifts between the contrasting portions of the field of view.

As will be gathered from the above experiment, visual fatigue is another manifestation of the same retino-cerebral process which gives rise to the effects of "persistence of vision".

Colour Fatigue.—Some effects of colour fatigue are often experienced. For example, when the eyes are closed for a time in bright sunlight and again opened, the apparent hues of surrounding objects are seen to be considerably changed. This is due to the fatiguing effect of the red light transmitted by the eyelids. Effects of this kind are not often noticed, however, unless the fatiguing light is of considerable intensity. The subject will be discussed more fully in the chapter on colour vision, but a simple experiment will illustrate the nature of the phenomenon. Protecting the eyes with a piece of ruby glass, gaze steadily at some bright source of light of fair dimensions, such as an incandescent gas mantle, for about one minute. Then quickly look without the glass at a yellow-coloured sodium flame produced by holding a piece of salt in the flame of a Bunsen burner. (The experiment should be performed in a darkened room.) The flame will now appear quite green. On the trichromatic theory of colour vision the ordinary yellow appearance of the flame is due to the simultaneous stimulation of red and

green colour sensations. When the red receiving apparatus is fatigued, the green sensation predominates. Positive and negative after images of coloured objects may thus be seen, the negative after image generally possessing a roughly complementary hue.

Sundry Visual Effects.—Apart from sensations of colour and light definitely due to retinal fatigue, some effects, which seem to be largely mental, deserve mention. The phenomena known as induction are very familiar; a number of grey patches of increasing darkness (each individual patch being, however, quite even in tone) when placed together give an effect of “fluting” due apparently to some mental accentuation of contrast. The effect seems of an order too marked to be accounted for by retinal fatigue, although this would act in a similar direction. There are also certain colour effects which appear to be almost entirely of mental origin. Edridge Green states that an eye after adaptation to darkness may be shown a piece of pale green paper and may estimate the colour as white if no other coloured objects are available for comparison. When the idea of such a white is acquired, other pale colours are estimated with regard to it—for example, a true grey may appear pink. Here again retinal fatigue would tend to act in the same *direction*, and the relative magnitude of the effects is difficult to estimate. Sunlight stealing through a narrow aperture into an artificially lighted room appears very blue. In such a case it would appear that retinal fatigue may be very largely concerned.

Simultaneous Contrast.—The effects of simultaneous contrast in modifying the appearance of colours are numerous and varied; they can only be forecasted approximately on the lines of the fatigue effects considered by the trichromatic theory. In the copying of nature these effects may cause an artist no little difficulty, until he acquires the power to consider and estimate each colour separately, either by artificial means or otherwise. The use of a small screen with an aperture is a useful expedient until the practised eye can recognize the true nature of a tint independently of its surroundings. Correctly used, the pigments will themselves reproduce very largely the delicate contrast effects with which nature is so lavish. In original painting, however, the successful colourist will learn how to enrich or diminish the contrasts of his hues. Complementary colours in contact will always enrich each other if the retinal areas concerned are sufficiently large. In this way the placing of a brown by the side of a bright red will tend to make the former look greenish; a purple by the side of red will appear more blue. It is very easy,

however, to waste rich colour, as is often done in weaving, by the employment of a pattern so minute that the general effect is a kind of colour summation on the retina, giving a grey. The success of certain painters renowned as colourists appears to be due more to their daring in the use of masses of colour rather than to any special skill in mixing or selecting paints.

To illustrate the same point in another way: it is common knowledge to the modern gardener that he can get a better effect in a flower garden by masses of bloom of the same hue rather than by the combination of the effects of many differently coloured flowers.

With his usual thoroughness, Abney has submitted the subject of simultaneous contrast to qualitative and quantitative examination. The colour-patch apparatus, or a modification of this by means of which two spectra are secured, was employed. The contrasting colours being thrown in juxtaposition on one small screen, the colours as apparently modified could be produced by mixing a spectral hue with white on another small screen at a distance of one foot. The following table is given to show the results of experiments on contrasts with *white*, and shows the apparent hue given to the white of about equal brightness as well as the modification produced in the contrast colour, ordinary vision being employed. Not only is the white modified; the spectrum colour is modified also.

CONTRASTS WITH WHITE

Uncontrasted Spectrum Colour.	Spectrum Colour as seen when contrasted with White.	Apparent Hue given to White.
Red	{ Cherry-red	Green-grey
	{ Scarlet	Bluish green-grey
Orange	Terra-cotta	Blue-grey
Yellow	Raw sienna	Light blue-grey
Yellow-green ..	Olive green	Amber
	{ Emerald green	Pinkish lavender
Green	{ Grass green	Light pink
	{ Blue-green	Dark pink
	{ Signal green	Salmon
Blue-green ..	Cyanine blue	Yellow ochre
Blue	{ Violet-blue	Brownish yellow
	{ Blue-violet	Dark greenish yellow
Ultramarine ..	Ultramarine	Raw sienna
Violet	Violet	Burnt sienna

Another numerical table by Abney shows a most remarkable feature, namely, that between $\lambda = .569\mu$ and $\lambda = .558\mu$ there is a sudden remarkable change in the nature of the contrast colour. Instead of the purple contrast which we should expect from the green on the basis of fatigue we find an orange! Subsequent experiments have verified the observation, but two points are to be remembered: firstly, that in the experimental arrangement adopted, one eye alone viewed the contrast and one viewed the matching colour; secondly, that the white was that due to the arc light.

As well as contrasts with white, contrasts between colours give certain striking effects, as will be seen by the following table, also given by Abney from the results of experiments with the double colour-patch apparatus.

Original Colours. Contrast.		Change due to Contrast.	
Red	Orange	Red becomes yellower	{ Orange becomes green- grey.
„	Green	„ unaltered but brighter	{ Green unaltered but brighter.
„	Blue	„ becomes more orange	Blue becomes greener.
„	Violet	„ „ orange	Violet—not changed.
Green	Orange	Green becomes bluer	{ Orange becomes yel- lower.
„	Blue	„ „ olive	{ Blue becomes more violet.
„	Violet	„ „ yellower	Violet becomes bluer.
Orange	Blue	Orange „ redder	Blue becomes deeper.
„	Violet	„ „ greener	Violet becomes bluer.
Violet	Blue	No marked change takes place in either.	

In seeking to apply the above results to cases in painting, &c., it must not be forgotten that the experiments were made with dark-adapted eyes and the colours were small, bright, contrasting patches. Fatigue effects would naturally be very marked, and would not be present to the same extent in ordinary vision in a well-lighted room, especially when no special attention is paid to the contrast. However, the table will be useful to colourists as showing the *tendencies* in each case, if they guard against assuming that (for example) every patch of orange placed against a red will become green-grey in appearance.

Effects of Intensity (Purkinje Effect).—The effect of intensity on the appearance of colours is another matter of great

importance to the painter. To understand this we must refer to the description of the Purkinje effect (p. 91).

It will be shown that the position of maximum apparent luminosity in the spectrum shifts towards the longer wave-lengths with increasing intensity of illumination. If, then, the eye views contrasting lights consisting respectively of ranges of wave-lengths in the blue-green and yellow-green parts of the spectrum, an equal increase of the intensity of both will cause an apparent increase in the relative intensity of the yellow-green. This effect is useful to imitate in painting, as we can convey the effect of high luminosity by imitating just such modification of the relative brightness of hues as would be suggested by the Purkinje effect, although one must be careful not to overdo it. Examples of this expedient are very common when pictures are closely inspected. Blues always take greater prominence when the light is of low intensity.

In concluding the present brief sketch of psychological colour effects, attention must be drawn to a last important point. It is not too much to say that the majority of persons often fail to appreciate colours accurately through self-suggestion. For example, snow appears white to them everywhere, although when lying shaded from the sun on a mountain side it will appear as blue as the clear sky above it. Shadows on sand (merely light brown to the ordinary person) give bewildering and delicate colour effects. It cannot be too often emphasized that colour lies in the light which illuminates an object and is not inherent in the object itself. It also lies partly in the brain which interprets the visual sensations, a statement which can hardly be doubted in considering the interesting changes of hue in spectrum colours caused by the admixture of white, to be described in the chapter on colour vision. It may be noted here that if a patch of ultramarine is viewed through a piece of thin white tissue-paper, its hue appears much warmer. Presumably the same effect will be found in painting when laying on a "scumble" of white over a blue.

CHAPTER VI

Colouring Materials

(This chapter aims at giving only the barest outlines of the subject.)

Colouring Materials.—It is manifestly impossible to deal in a single chapter with such a vast subject as that of colouring materials. We should have to consider in detail important branches of the work of the artist, the dyer, the printer, the glass worker, the decorator, and the potter, to mention a few only of the numerous branches of the arts and manufactures in which colouring materials are employed. Nevertheless, colouring materials may be roughly grouped into a few classes.

1. The pigments, largely consisting of coloured earths, stable chemical “salts”, and metallic oxides. (There are also a few pigments of vegetable origin.) They are generally opaque, and give their colour effects to the surface on which they are spread by reflected light.

2. The materials, often metallic oxides, which are employed for the colouring of glass and pottery by fusion into the mass or surface of the substance. In such cases the final colour may be due to a metallic silicate, or to a colloidal precipitation of the reduced metal in the mass, or again to the transmission of light through a thin film of reduced material. The final colour is not connected, necessarily, with the colour of the original substance.

3. The “dyes” and “lakes” which give their colour in solution. These are generally “organic” compounds. A few are derived from plants, but the majority are prepared from the by-products obtained in the manufacture of coal gas. The dyes are, of course, employed directly for the colouring of fabrics, &c., but in order to use these colours as pigments it is necessary to employ a solid white “base” such as aluminium hydrate.

We can now proceed to consider these colouring materials and the manner of their use in a greater detail.

Pigments and Painting.—For the purposes of painting it is necessary to use a medium in which the pigment may be brushed on the surface which it is desired to colour. For water colours, the pigment may be applied in a weak solution of gum arabic. Generally speaking, the pigment and medium are sold mixed together, either solid in cakes or moist in collapsible tubes. Gelatine solution is another useful medium for water paints, especially when it is desired to lay on the pigment very thickly, but a better medium for painting with opaque pigments, when oil is not desired, is white or yolk of egg with vinegar. Both gum and gelatine may be rendered insoluble by the admixture of a little potassium bichromate to the solution before drying. The insolubility is produced by exposure to light, this action being the basis of the well-known method of gum-bichromate photographic printing, and one or two allied methods.

Water colours are sometimes employed in opaque layers and even for decorating work in “distempers”. In pictures the light from the paper ground shines through the paint and may be made to produce very luminous and beautiful effects. Water colours are very useful for quick sketches on account of the rapid drying of the colours. The change of the nature of the surface in drying, however, is responsible for one great difficulty in water-colour painting. The reflection of light from the smooth water surface, when wet, is specular, and this white light is generally avoided by the eye. The colour of the paint is then seen mostly by the transmission (through the particles of pigment) of the light, which suffers diffuse reflection at the surface of the white paper beneath. When the surface dries, however, the specular reflection vanishes, and light is now also diffusely reflected from the surface of the paint, thus producing a considerable change in appearance. This is naturally in the direction of diminishing saturation. The technique of water colours is thus rather difficult as far as the production of definite and accurate colours is concerned. The use of a paper with a roughened surface (such as “Whatman” paper) is usual for water colours, because the light strikes the elementary small areas on the “hills and dales” of the paper at greater angles with the normal. This secures a more diffuse reflection even from the wet surface and also produces a greater saturation of colour, as the light travels obliquely through the layer of paint and thus through an increased thickness of colouring matter. It may be noted that artists should never work with water colours in a room where the light falls very obliquely on their work,

as, when turned to the light, the colour will appear more pale and unsatisfactory.

In oil painting the pigment is mixed with a drying oil such as linseed or poppy oil, thinned, if necessary, by turpentine. The surface of such a paint when dry may be made quite matt. If a harder shiny surface is required for decorative work, a certain amount of varnish¹ may be added to the paint, thus making the ordinary "paint enamels". Harder surfaces (on metal work, &c.) are secured by the "stoving enamels", which have to be baked after painting. The surface of an oil painting is generally varnished to protect it from the air and from abrasion. The effects of oil colours are not nearly so much altered in drying as those of water colours.

Precautions in Mixing Pigments.—As colours are intimately mixed in painting, some knowledge of their composition and stability singly and mixed is very desirable for a painter. Turner was especially prone to use unstable colours, and many of his pictures are now spoilt. In the addendum to the present chapter the more familiar pigments are grouped according to chemical classification. The following three points with regard to *mixing* the pigments are most important.

1. The safest mixtures are of the oxides and hydroxides. These are generally inert in themselves.

2. Sulphides such as cadmium yellow should not be mixed with pigments containing iron, lead, or copper, otherwise the black sulphides of these latter may be formed.

3. Highly oxygenated salts such as the chromates (lead chromate or chrome yellow for example) should not be mixed with organic pigments which may reduce the chromate. There is marked action in the case of chromates mixed with yellow lakes, cochineal lakes, or indigo, &c. Mixtures containing ferric hydrates and organic pigments should not be trusted.

Stability of Pigments.—Although the above precautions in mixing are few and easily observed, the instability of many of the pigments by reason of the effects of light and air is in reality a more serious difficulty. With the idea of developing definite information

¹ "Varnish" is composed of a resin dissolved in alcohol (spirit varnish), turpentine, or oil. The resins are amber, copal, dammar, mastic, sandarac, shellac, and common resin. Mastic in turpentine is generally used for varnishing pictures, and copal dissolved in hot linseed oil may be used for modifying the consistency of oil paints.

as to the relative stability of pigments in water colours, investigations were conducted by Russell and Abney (*The Action of Light on Water Colours*, H.M. Stationery Office, 1888).

The first tests were on pieces of Whatman paper which had been coloured by successive washes of the pigments, producing areas covered once, twice—to eight times. The papers were exposed to the outdoor air and sunshine in tubes so that moist air but *no rain*

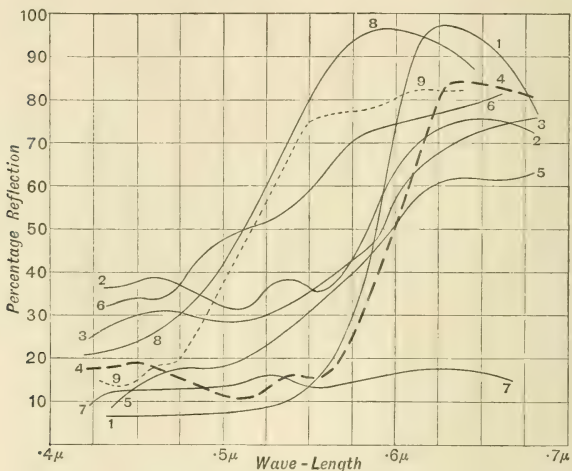


Fig. 26.—Spectral Reflecting Powers of Pigments

1, Vermilion. 2, Carmine. 3, Indian red. 4, Crimson lake. 5, Burnt sienna. 6, Burnt umber. 7, Sepia. 8, Cadmium yellow. 9, Gamboge.

could enter, the first exposure being from May, 1886, till March, 1888. After this the specimens were placed in the dark.

The results are given in a table in the paper. (It was found that the carmine had completely bleached away.) Prussian blue and Antwerp blue had been considerably bleached, but they recovered to a certain extent when kept in darkness. Various other tests of a similar nature on the effect of light alone, &c., were made, also on the effects of the mixing of certain colours. Many colours are thus especially susceptible to the attacks of moist air and light, (Dry air is much less dangerous.)

An interesting description is given in the *Journal of the Royal*

Society of Arts (for 5th May, 1922) of a series of experiments carried out by the late Mr. Holman Hunt on the permanency of artists' oil colours. Some of his methods of using sensitive colours between layers of varnish seem to be extremely valuable.

Action of Pigments on Reflected Light.—Figs. 26 and 27 illustrate the spectral reflecting powers of a number of pigments, and should prove of interest to artists. Note the low reflection in the

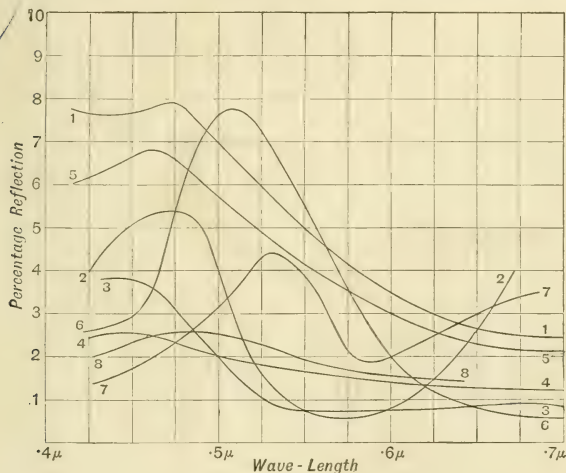


Fig. 27.—Spectral Reflecting Powers of Pigments

1, Antwerp blue. 2, Cobalt. 3, Ultramarine. 4, Indigo. 5, Prussian blue.
6, Emerald green. 7, Chromium oxide. 8, Terre verte.

blue given by vermilion. It is useless to mix it with blue to form a purple. Crimson lake is the more suitable. Note, too, the high reflection in the green given by cadmium yellow and gamboge—they form good “subtractive” greens as far as colour is concerned, but these will never be as luminous as emerald green. Note the low reflection of “terre verte” in comparison with emerald green.

Ultramarine reflects very little in the yellow and red regions of the spectrum, although the curve is seen to rise slightly towards the red. It is less efficient than other blues (Prussian blue) in making violets and purples by mixture with crimson.

Colouring Materials for Glass, Pottery, and Enamels.—

The colouring of glass by the fusion of certain metallic salts in the mass or in the surface is a very ancient art, and reached a high level probably on account of ecclesiastical requirements in stained-glass windows.

Pink tints may be produced by manganese. Yellow and red tints are produced by nickel added in various amounts, and also by the addition of sulphur and selenium. Olive-green tints are generally due to chromium or iron; blue-green to copper; blue-violet to cobalt; and neutral or grey tints to mixtures of nickel, manganese, iron, and cobalt. Gold may be used for ruby glass. Iron is one of the commonest impurities in sands used for bottle glass making, and the greenish coloration is due to this cause. Pure sand free from iron is naturally very highly prized. For common table ware, however, the addition of a little manganese to the glass counteracts the greenish appearance. Selenium may also be used, but glasses containing selenium are said to become brown under the influence of light.

Crookes¹ has made an interesting series of experiments to investigate the properties of a number of glasses prepared according to definite formulæ. He found that the fusion in the glass of some of the rarer metallic oxides, including didymium, produced an opacity to ultra-violet light much greater than that of ordinary glass, without altering greatly the colour of the light to the eyes. Such a glass is obtainable for the protection of water-colour pictures, and for spectacles.

He also produced a glass in which the green colour was due to iron in a ferrous condition, derived from ferrous oxalate, and prevented from oxidation by the judicious addition of tartar and wood charcoal to the fused glass. This glass has a very high absorption for the infra-red, and would be especially useful for workers with furnaces, &c. Exact information as to the absorption of certain glasses of definite composition has been given by Szigmondy.² In this case tables of absorption coefficients are supplied. Curves of spectral absorption for various types of glare-protecting glasses have been given by the present writer.³

Glasses for Eye Protection.—Coloured protective glasses are very necessary for many industrial purposes, such as arc lamp

¹ Crookes, *Phil. Trans.*, A. Vol. CCIV, 1914.

² *Ann. der Physik*, 4, 60, 1901.

³ *Trans. Opt. Socy.*, Vol. XVIII, April, 1917.

work, acetylene welding, and furnace work. Deep blue glass is commonly employed (preferably that coloured by copper).

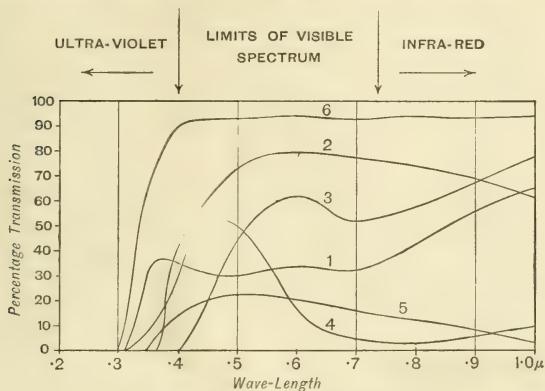


Fig. 28.—Transmission of Coloured Glasses

1, Neutral glass (a). 2, Light fieuzal (green tint). 3, Dark fieuzal (green tint). 4, Signal green. 5, Crookes's green glass (246). 6, Ordinary colourless glass.

Figs. 28 and 29 illustrate the spectral transmission of several glasses in the ultra-violet, visible, and shorter infra-red regions of

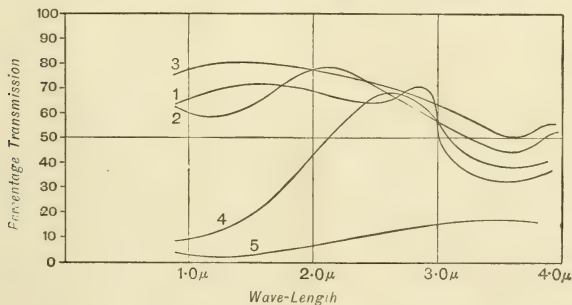


Fig. 29.—Transmission of Coloured Glass in the Longer Infra-red Regions

1, Neutral glass (a). 2, Light fieuzal. 3, Dark fieuzal. 4, Signal green. 5, Crookes's green glass (246).

the spectrum. Note the efficiency of the light fieuzal in absorbing the ultra-violet. Crookes's glass 246 (blue-green in hue) is seen

to be especially efficient in absorbing the infra-red or "heat rays", as is also the signal green (copper) glass. Many neutral glasses transmit more efficiently in the ultra-violet and infra-red than in the visible part of the spectrum. The exact cause of the "colour" in glass of this kind is a very interesting subject. Wood, in his textbook on *Physical Optics*, describes experiments on the optical resonance which may take place in thin metallic films deposited on glass, where the size of the resonating particles is at least comparable with that of the wave-length of the light. Garnett¹ gives a discussion of the possible explanation of the colours of stained glasses on the lines of optical resonance. The metal (in the colloidal state) is supposed to be distributed in small globules in the mass. The presence of such particles has been substantiated by the work of Siedentopf and Szigmondy by an "ultra-microscopic" method, in which the particles are detected by the "diffraction discs" they produce under very intense illumination.

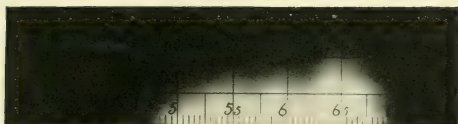
Advantage is taken also in pottery-making of the varied and beautiful effects produced by thin metallic films, especially in the best examples of "lustre" ware.

The production of glass of very definite colour properties has up to the present been difficult, but the chief difficulties are now said to be overcome. These have been very largely bound up with the securing of the (usually necessary) chemical "reducing" actions in the melted mass. Vegetable hydrocarbons are often employed to prevent oxidation. The securing of satisfactory results is dependent on the uniformity of the size of the colloidal particles.

The Dyes.—Hardly more than a passing reference can be given to this subject, which is practically a science in itself. In 1856 Sir W. N. Perkins produced the dye *mauve* from aniline, a coal-tar product. The subject developed rapidly. In 1869 Graebe and Liebermann succeeded in producing *alizarin*, the essential colouring matter of the madder root, from anthracene. Distinct series of dyes have been evolved from benzene, naphthalene, and anthracene, but it is not within the scope of this book to go into the chemistry of the subject. Many useful dyes, such as indigo, were originally purely vegetable products, but can now be produced synthetically.

The method of using the dyes for colouring fabrics or yarn

¹ *Phil. Trans. Roy. Soc., London, A. Vol. CCIH, p. 385.*



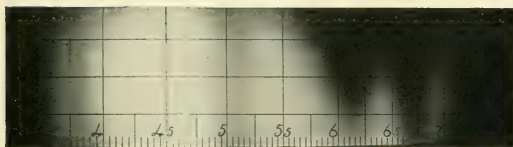
A



B



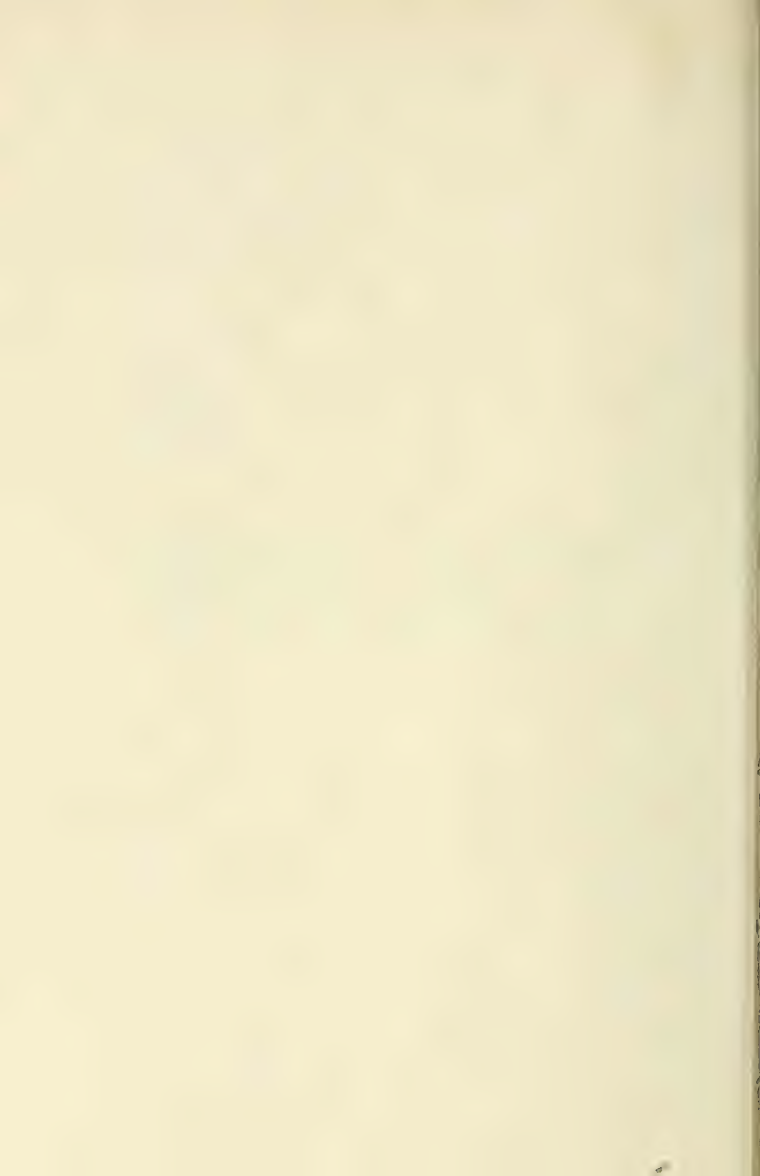
C



D

- A }
 B } Wratten "Haze Cutting" Filters. See Appendix, p. 182.
 C }
 D Methylene Blue Dye.

FIG. 30.—ABSORPTION SPECTRA SHOWN BY THE WEDGE METHOD



varies with the nature of the fibre. Wool takes dyes most readily and cotton least, silk being intermediate between the two. The method of dyeing also depends, very naturally, upon the probable after treatment of the material.

Wool may be dyed directly in an acid bath with certain colours, but cotton will not generally respond to such treatment. Cotton fibres are treated with a *mordant*, such as tannic acid and stannic chloride, when they may be dyed with the "basic colours", the colouring material being deposited in an insoluble "lake" on the fibres of the material by the action of the mordant. There are some substances, however, which will dye cotton directly, and some which need a mordant with any fibre. In some cases the colours (developed colours) are produced on the fibre by the *successive* application of the necessary constituents.

(The most unsatisfactory feature of many of the dyes is their unstable and fugitive nature. Very few (comparatively speaking) are capable of withstanding any continued exposure to light and air. One of the chief faults, from the public point of view, of the supply of dyed materials is the frequent absence of any accompanying information as to the relative stability of the different colours, information which is a commonplace to the dyers themselves. It would be far more satisfactory to be able to choose even from among very few really *fast* colours if necessary.

The spectral absorption of many dyes has been measured by Uhler and Wood and published in their *Atlas of Absorption Spectra* (Carnegie Inst., Washington). There is another chart of absorption spectra of dyes due to Kenneth Mees (Longmans, Green, & Co.).

The spectra are photographed through a cell containing in solution a dye in definite strength, and in order to exhibit the type of absorption the more completely a wedge, of "neutral" tint and of gradually increasing absorption in the direction parallel to the slit of the spectrograph, is also inserted in the beam of light. The dye itself is also sometimes inserted in a wedge cell.

The general appearance of the photographs is shown in fig. 30, and the height of the white portion of the photograph at any wave-length indicates the relative transmission of the dye at that point. Due allowance must naturally be made for the variations caused by residual colour in the wedge, the luminosity variation in the spectrum of the source, and also the spectral sensitiveness

variations of the plate. Information as to the origin and relative stability of the dyes is also given.

For accurate purposes a percentage transmission table is doubtless to be preferred, but the photographs show the type of absorption very well.

Colour filters for laboratory purposes can be made very well from dyed gelatine films. These are manufactured in convenient form by the Kodak Co. (Wratten division), and a booklet is obtainable which gives numerical data as to spectral transmission, as well as photographs taken by the method described above.

A colourist will readily understand how, from a study of their percentage transmissions, he may forecast exactly the results of mixing dyes which do not interact chemically. Care should be taken to avoid dichroic mixtures and those which have a low transmission in most parts of the visible spectrum and a sudden increase in transmission in the extreme red.

ADDENDUM TO CHAPTER VI

Chemical classification of pigments and tables of stability.

1. ELEMENTS.—Carbon as *ivory black*, *lamp black*, *charcoal black*, *Indian ink*, *graphite*; gold, silver, aluminium, platinum. Finely divided metal can be used as a pigment, *aluminum paint* being common. *Silver* is easily tarnishable.
2. OXIDES.—*Chinese white* (zinc oxide), green chromium oxide, *burnt umber* (iron and manganese oxides), *cobalt green* (cobalt and zinc oxides), *cobalt blue* (cobalt oxide and alumina), *cæruleum* (cobalt and tin oxides). The *ochres*, including *Venetian red*, *light red*, *Indian red*, and *burnt sienna*, which are ferric oxide in various forms. *Red lead* (oxide of lead). This is not so inert.
3. HYDROXIDES.—The native earths including *yellow ochre*, *raw umber*, *raw sienna*. These are hydrates and oxides of iron and manganese mixed with some white clay or heavy spar (barium sulphate). *Viridian* (emerald oxide of chromium).
4. SULPHIDES.—*Cadmium yellow*, or *aurora yellow* (cadmium sulphide), *king's yellow* and *realgar* (sulphides of arsenic), *antimony red* (antimony sulphide), *vermilion* (mercuric sulphide). This is said to be liable to blacken in water-colour drawings.

5. CARBONATES.—*Emerald green substitute* (copper carbonate and alumina), *malachite green* (natural copper carbonate), *white lead* (lead carbonate and hydroxide), *whitening* (calcium carbonate).
6. SILICATES.—*Terre verte* (a native mineral silicate of iron, magnesium, and potassium).
7. CHROMATES.—*Chrome yellow* and *chrome red* (chromates of lead). The chromates of barium, strontium, and zinc may also be used.
8. VARIOUS.—*Cobalt yellow* (cobalt potassium nitrite, $K_2Co(NO_2)_6$ and water). *Naples yellow* (lead antimonate), *tungsten green* (chromium tungstate), *cobalt violet* (mixed arsenate and phosphate of cobalt). *Baryta white* (barium sulphate). *Schweinfurt green* (basic copper arsenite). *Ultramarine* (artificial), made from soda, sulphur, charcoal, and china clay heated in a furnace. *Freeman's white* (lead sulphite). *Permanent violet* (phosphate of manganese).
9. ORGANIC COMPOUNDS.—*Verdigris* (basic copper acetate), *emerald green* (basic cupric aceto-arsenite). *Indian yellow*, *gamboge* (a gum resin), *sap green*, and *indigo* (all of vegetable origin). *Prussian blue* (prepared by precipitation from a ferric salt with potassium ferrocyanide). *Antwerp blue* is Prussian blue mixed with a white base. *Bitumen*, *bistre*, *sepia*, *Vandyck brown*. The lakes: *Indian lake* (from a resin), *carmine*, *crimson lake*, *purple lake* (from the cochineal insect). *Alizarin red* and *rose madder* (from the root of the madder plant, or prepared synthetically). *Yellow lakes* from quercitron bark.

Modern catalogues of pigments, such as the one issued by the firm of Winsor & Newton, often contain very complete information as to the relative permanence and stability of artists' colours. Somewhat different conditions hold between oil and water colours, as the oil medium acts as an organic reducing agent in certain cases, thus making the use of chromates in oil painting somewhat dangerous, whereas they might be quite safe as water colours. Again, pigments which are little affected by the ordinary weathering agencies of light, dampness, and air may be especially liable to the attacks of the sulphuretted hydrogen usually found in the air of a town of any size.

(Generally speaking, the "earth pigments" are the most stable and satisfactory.) While it is not possible to give complete information as to the properties of all the varieties found in commerce, the following lists will give an idea of the general grouping of colours as to stability and permanence.

TABLE OF OIL- AND WATER-COLOUR PIGMENTS

CLASS A.—Thoroughly permanent under ordinary conditions

WHITE.—

Chinese white or zinc white.

RED.—The earths, including—

Light red.

Venetian red.

Indian red.

Mars red, &c.

ORANGE, BROWN, AND YELLOW.—

Yellow and other ochres.

Raw sienna.

Mars orange.

Cappagh brown.

Burnt sienna.

Raw umber.

Burnt umber.

Mars brown.

Cadmium yellow.

Aureolin.

Cobalt yellow.

Permanent yellow.

Lemon yellow.¹

GREEN.—

The green chromium oxides.

Viridian.

Cobalt green.

Terre verte.

Veronese green.

BLUE.—

Ultramarine and its varieties.

Cobalt blue.

Cœruleum.

Smalt (water colour).

VIOLET.—

Cobalt violet.

Permanent, or mineral violet.

GREYS and BLACKS.—These are often pulverized stone or carbon products, and are generally quite permanent.

The chief disability from which this list of permanent pigments suffers is appreciated when the hues of the subtractive primaries are remembered: purple or crimson, yellow, and blue. There is not a satisfactory crimson or cerise in the list. A good range of yellows and orange-red is found, but not a good scarlet; also a range of blue-greens, blues, and violet, but not a selection of the more yellowish greens.

In order to meet the demand for crimson the colours derived from the madder root are used, the essential colouring matter being *alizarin*, which can be produced synthetically (from coal-tar products). The brilliance of the coal-tar dyes has always been a temptation to artists, but the use of such materials is not often permissible where any permanence of colour is desired.

There are, however, certain vegetable colouring materials, and a few of the synthetic dyes, which maintain a fair degree of permanence and may be safely employed, especially if they are protected from damp and the atmosphere as much as possible when used as

¹ Better as water colour than oil colour.

water colours. We may summarize these and certain other materials in

✓ CLASS B.—Pigments of fair permanence

WHITE.—

Flake white or white lead, *o* *.

RED.—

The vermilions.

ORANGE, BROWN, AND YELLOW.—

Indian yellow, *w*.

Gamboge, *w*.

Sepia, *w*.

Brown madder.

Vandyck brown, *x*.

The chrome yellows, * †.

GREEN.—

Hooker's green, *w x*.

Emerald green, *.

Alizarin green.

Malachite green, *x*.

BLUE.—

Prussian blue.

Antwerp blue.

VIOLET.—

Violet carmine, *w*.

PURPLE AND CRIMSON.—

The madder colours.

Rose madder.

Madder carmine, &c., *w*.

Synthetic alizarin colours, including permanent crimson, &c.

x Indicates the more doubtful colours.

w Indicates a colour more permanent as water colour.

o Indicates a colour more permanent as oil colour.

* Indicates a colour liable to the attacks of sulphuretted hydrogen, but otherwise permanent.

† Indicates a colour liable to reduction by the oil medium in oil colours.

Besides these pigments of lesser permanence there are also certain others which experience has proved to be of a fugitive nature.

The chief of these are: the carmines, crimson lake, brown pink, Italian pink, mauve, magenta, sap green, indigo, yellow lake, asphaltum. There are sundry mixed pigments which are of doubtful stability and permanence, among which the chrome greens and cinnabar greens, mixtures of lead chromate and Prussian blue, are the chief. Several factors unite against the permanence of such mixtures: mutual interaction, the action of sulphuretted hydrogen, and the reducing action of oil.

It may be given as a general rule that the permanence of a colour is not usually improved by mixing it with white or another colour, even when interaction does not take place.

In selecting a range of colours for the palette, the artist must consider several factors, permanence, possibility of reproducing all required colours by mixing without danger, luminosity and value

of the original colours, and lastly, but not least, the cost. Messrs. Reeves suggest that the following colours will fill most requirements for oil painting:

Flake white, lemon yellow, mid. cadmium yellow, yellow ochre, raw sienna, Venetian red, scarlet vermilion, rose madder, alizarin crimson, burnt sienna, brown madder, burnt umber, ivory black, cobalt violet, ultramarine, viridian.

Nisbet (*Oil Painting*) adds to these aureolin, Antwerp blue, terre verte, and Caledonian brown.

The earth pigments are relatively inexpensive; the most costly pigments in the list are lemon yellow, mid. cadmium yellow, rose madder, cobalt violet, and aureolin. Of the pigments in the above selection of Messrs. Reeves and Mr. Nisbet it will be noticed that two subtractive primaries, crimson and yellow, are mainly represented by the more expensive colours, so that it is hardly possible to provide a satisfactory palette without the use of these.

The only precautions to be observed (in order to secure permanency) in mixing with this selection are:

Aureolin is not to be mixed with madder or alizarin.

Antwerp blue is not to be mixed with vermilion, cadmium yellow, or lemon yellow.

Flake white is not to be mixed with cadmium yellow.

There are naturally many other pigments which are available and may be used with perfect safety. The above list should be taken rather as indicating the minimum requirement for ordinary work, if a wide range of colours which are to be reasonably permanent is desired.

Cheap oil-colour boxes generally contain chrome yellow and crimson lake; also sap green. All of these should be avoided if possible, except for non-permanent studies.

A similar list with a few modifications will serve for water colours; gamboge is a useful yellow, although not absolutely permanent, and may advantageously replace the more expensive cadmium and aureolin.

PART II

CHAPTER VII

The Eye and its Reactions to Light; Photometry

Construction of the Eye.—Before going further into the discussion of instruments or colour measurements it is necessary to study some of the main facts regarding vision. For a description (from the optical standpoint) of the various parts of the human eye reference may be made to any textbook of physiological optics, such as Laurance's *Visual Optics*¹.

We shall regard the eye simply as a camera-like instrument, with refracting arrangements to produce upon the retina sharp images of external objects. Such objects naturally can only be seen by virtue of their contrast one against another, firstly as regards light and shade, and secondly as regards hue. Thus we may regard all seeing as dependent on the photometric and colorimetric powers of the retina.

Fig. 31 shows a diagram of a section of the retina. The light first passes from the "vitreous humour", which fills the space between the lens of the eye and the retina, into a layer of "optic fibres" and nerve cells, which are practically transparent and insensitive to light. These comprise the layers 2-7 in fig. 31.

The functions of the several parts are at present unknown, but it seems probable that the layers are concerned with the collection of the nervous visual impressions from the light-sensitive layers beneath.

Underneath the several nerve layers are found the "rods and cones", which appear to be the true organs of perception.

Their general shape is appreciated by reference to the diagram.

¹ Or to *The Eye*, by Lionel Laurance. Ortho. Press, 1908.

The rods and cones are packed closely together, and each cone subtends an angle of about one minute at the posterior nodal point of the eye.¹ It is estimated that the retina contains about three million distinct cones, and about five or six times as many rods.

The rods and cones possess two distinct parts, the inner and outer limbs, the outer limbs being cylindrical and conical respectively. In each case they contract to a fine fibre connecting with a nerve.

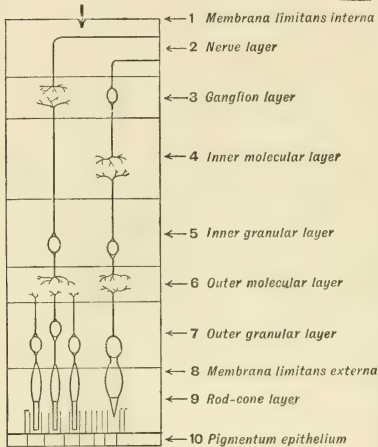


Fig. 31.—Diagram of a Section of the Retina

The rod cylinders are coloured with a pinkish substance (the visual purple) which is bleached by light. The rod-and-cone layer rests upon a layer of pigment cells containing a black pigment (*Pigmentum epithelium*).

The cells layer sends up fine processes between the rods and cones, “insulating” them from each other, and the presence of these black pigment cells probably plays an extremely important part in the machinery of the “adaptation” of the eye to different degrees of brightness of light.

The eye can work satisfactorily under a range of external conditions in which the general proportions of brightness of light vary as a million to one. This is far more than can possibly be accounted for by the well-known contraction of the iris under the stimulus of light. Adaptation for wide differences of illumination takes an appreciable time to complete, more especially in changing from bright light to comparative darkness, the sensitiveness of the eye continuing to rise for about an hour in certain cases.

At the centre of the retina is found the “macula lutea” or yellow

¹ The nodal points of a lens are points on the axis such that a small image subtends the same angle at the posterior nodal point as the corresponding object subtends at the anterior nodal point.

spot. This is oval in shape and subtends an angle of about 6° by 4° at the posterior nodal point. The cones are here relatively more numerous towards the centre, and the rods disappear entirely in the "fovea centralis", which is the seat of "sharp" or "distinct" vision. The fovea subtends an angle of approximately 1° . The yellow colouring of one of the outer layers of the retina at this place gives the yellow spot its name, and this yellow region is always causing difficulty and misunderstanding in colour measurements, so it is important to remember.

It is estimated that the optic nerve going to the brain contains about one million "insulated" nerves, which are capable of transmitting separate impulses. This leads to the conclusion that, although very likely each cone in the fovea has a separately connected nerve, yet in the outer regions of the retina there must be a great deal of interconnection between the sensitive elements. This accords well with the universal experience of indistinct vision away from the point immediately under observation or, in other words, not directly focused on the fovea.

As it is easy to show that the "macula" region of the retina is less sensitive to light than the surrounding regions, it is natural to ascribe the greater sensitiveness to the rods, and to assume that these are responsible for the colour-less vision which we experience when the light is of a low intensity. The cones are regarded as the components which yield the chromatic sensations.

Von Kries regards the trichromatic visual response, i.e. the power of the eye to differentiate sensations caused by lights of different colours, as applying to the cones alone. As far as is at present known, it appears that the rods alone are concerned with the secretion of the "visual purple". The differentiation of the visual functions of the rods and cones seems now to be regarded as removed from the realm of theory into that of established fact, although it is true that some physiologists still doubt the conclusion owing to the absence of physiological evidence.

As the intensity of light is diminished, the red sensation is the first to disappear, leaving the greens and blues (of equal brightness) still visible as hues, while the blue sensation is the last to vanish. The colour-less or achromatic vision, which is experienced in the peripheral retinal regions, does not occur at the fovea, for colours are, in fact, recognized at the foveal "threshold of vision". (See a later paragraph.)

Colour Fields.—The whole of the retina is not "colour-

sensitive", and the angular extent of the sensitive portion may be measured by an ordinary "perimeter", which consists of a metal band or arc bent to an arc of a circle, at the centre of which the eye is placed. Measurements of the colour fields are generally made when the eye is dark-adapted. The eye "looks" steadily towards the mid-point of the perimeter, and a spot of coloured light is moved along the arc (which is graduated in degrees) till the sense of its colour vanishes. The arc may be placed of course in any desired orientation, and the entire extent of the

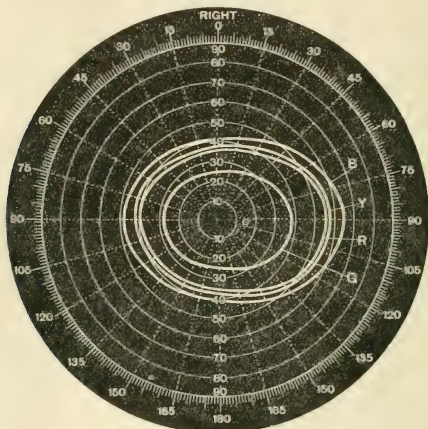


Fig. 32.—Colour Field for Right Eye

colour-sensitive portion may thus be mapped out. The diagram (fig. 32), which is self explanatory, shows the extent of the field for different colours for a normal right eye. The fields are considerably increased when the intensity of the light is increased.

Ferree and Rand¹ state that: "The far periphery of the retina is not blind to red, blue, and yellow. It is merely deficient in sensitivity to these colours. That is, with stimuli of sufficient intensity the limits of red, blue, and yellow coincide with the limits of white light vision. The blindness to green, however, is for our observers absolute. The amount of change of intensity required to produce a detectable change in the apparent limits of sensitivity in the more remote parts of the retina is very great.

¹ *Amer. Jour. Physiol. Optics*, July, 1920.

The shape of the zone of sensitivity to a given colour changes with the intensity of the stimulus employed in making the determination."

Non-achromatism of the Eye.—The eye is a simple non-colour-corrected refracting system. Since the shorter wave-lengths suffer the greater deviation, the violet and blue images are formed nearer to the lens than the yellow and red. The obscuring of a portion of the iris of the eye with a card reveals colour effects in images showing strong contrast (window bars, for example). Certain books state that blue light requires less accommodation for focusing than red light, and thus "stereoscopic" colour effects may be seen between objects at the same distance from the eye if they are illuminated separately by red and blue light. If the effect depends on accommodation, and not on convergence, the direction of the relative displacement might be indefinite, but the blue (to *binocular* vision) appears unexpectedly in front of the red. These effects are often seen at the theatre. Chromatic parallax arising in this way may cause serious difficulty in setting the crosslines in the eyepiece of a spectroscope on a spectrum line, unless they are viewed by light of the same wave-length as that of the line.

Visual Measurement and Comparison of Brightness.—It is well known that the eye alone cannot give satisfactory quantitative measurements of brightness, even when a standard of brightness is available.

Although we may obtain a kind of natural measure of sensation on the assumption that each step of just perceptible brightness increase adds an equal quantity of sensation, yet in ordinary work we measure a sensation in terms of the stimulation. Hence the term "brightness" refers (in dealing with a sensation due to any one monochromatic light) simply to the relative *energy* received by unit area of the retinal image of a source of light. This does not cover the meaning of the term in all cases, but it is sufficient to think of brightness in this way when trying to alter it in a quantitative manner. Provided then that we restrict colour matches to those made between lights of the same spectral composition, our photometric work will give energy comparisons, but this is not necessarily the case when comparing the "brightness" of differing hues. The "brightness" of coloured light refers to the brightness of white light producing an equal sensation of luminosity to the eye.

The basis of exact photometry is the power of the eye to detect very small differences of brightness between two sources, such

as small, evenly illuminated rectangles; these are placed very close together, so that, should the brightness of the two be equalized, the boundary contrast disappears. Therefore, when comparing the brightness of two unequal sources, it is necessary to vary the brightness of one or both in a known proportion until equality is attained, and then the original relative intensities may be calculated. For best results it is found that the photometric field should subtend an angle of 3° to 5° at the eye, and the brightness should not exceed (nor fall below) certain definite values which can be found from the results of Königs and Brodhun, to be described later (p. 89).

It is now necessary to conceive of a quantitative means of measuring light, considered solely as the agent producing the sensation of brightness.

We assume that the quantity of light is constant for every cross section of a tube whose sides are made up of rays of light, excluding effects of reflection and absorption. Provided the spectral composition remains unchanged, the quantity of light will thus be proportional to the energy passing through such a cross section in unit time. There are certain means which enable us to vary the light received from a source (and therefore the brightness of an object illuminated by it) in a definite proportion.

“Inverse Square” Law.—If a small source of light be radiating uniformly and steadily, the amount of light radiated into a definite solid angle will be constant. The solid angle subtended by a small screen at a fair distance from the source, and normal to the incident light, is inversely proportional to the square of the distance. Hence the amount of light received by the screen (with those reservations) is inversely proportional to the square of its distance from the source. This is the fundamental way of varying intensity of radiation. The brightness of the screen *as seen by an eye in a fixed position relatively to it* is proportional to the amount of light falling on the screen, and thus follows the same law.

Rotating Sector.—If an opaque disc, having an angular sector removed, be rotated very rapidly, it is found that the effect of flicker, caused by the intermittent passage of light through the aperture, ceases when the angular velocity attains a certain value. The *apparent* steady brightness of a source thus seen, by reason of the phenomenon of persistence of vision, is directly proportional to the angular value of the sector opening.

This law, which has resulted from a great deal of experimental¹

¹ Talbot and Plateau, *Lond., Ed., and Dub. Phil. Mag.*, v, 327, 1834

work, has been shown by Abney and Hyde to hold good over all experimental ranges of brightness. The accuracy falls off if the angular aperture of the sector is reduced below 10° . In one form of variable sector the aperture can be raised at will during rotation, a great convenience in photometric adjustments (see fig. 33).

Changes of Aperture.—In spectrum work the brightness of the continuous spectrum may often be controlled by varying the slit width. This brightens any spectral region proportionally to the said width, which can be indicated by a delicate micrometer

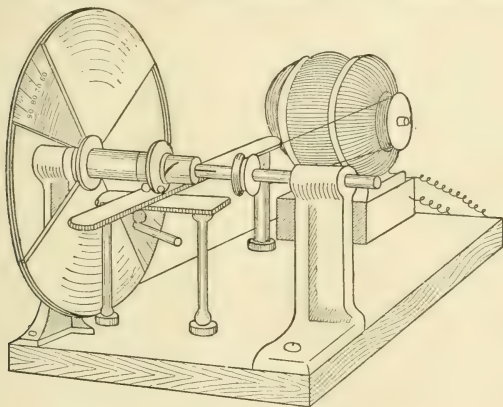


Fig. 33.—Sector of Variable Angle

screw. Naturally this expedient is limited in its use by considerations of the decreasing purity of the spectrum when the slit is widened. In some cases the length of a slit may be adjustable.

Adjustable diaphragms are often used in conjunction with a lens system which forms an image, the brightness of which is thus made proportional to the area of the aperture or "stop".

Photometric Wedges.—Wedges of very small angle ("cast" from suitable steel moulds in gelatine, which holds lamp-black in suspension) have been widely used in photometric work. In annulus form they were employed in Abney's researches in colour vision, when circumstances rendered the use of a sector undesirable (see fig. 34). Mounted on glass, they scatter little light, and, when moved in front of a small aperture, they afford an extremely convenient means of varying the brightness of a beam passing through

it. A preliminary calibration which gives the brightness in relation to the scale reading is necessary to each wedge. As would be expected, the relation is nearly logarithmic.

Good even wedges of this type may be copied photographically, and "photographic wedges" made in this manner are used in

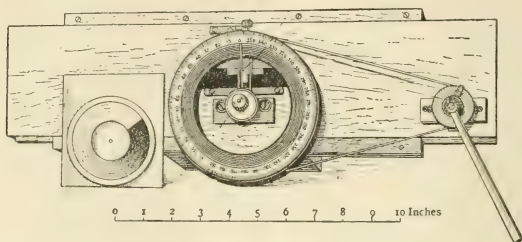
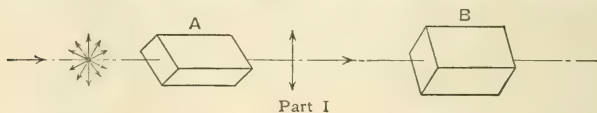


Fig. 34.—Annulus

plate sensitometry;¹ also wedges ground from neutral-tinted glass are employed. The brightness of the transmitted light no longer follows the logarithmic law in the case of the photographic "wedges".

Polarizing Prisms.—A prism of Iceland spar, such as one of the Nicol or Glan-Thompson types, has the property of transmitting



Part I

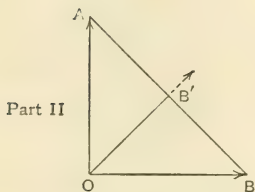


Fig. 35.—Polarizing Prisms crossed—
all light stopped by B

only those components of the light of which the "vibrations" are parallel to a definite direction. Referring to fig. 35 (Part II), imagine that light is caused to pass through two such prisms in succession. The first transmits only vibrations parallel to some direction OA. (Imagine that light is coming towards you from the diagram.)

If the second transmits only vibrations parallel to OB, no light can pass through the combination. If, however, the second transmits components parallel to OB', then the amplitude of the vibration

¹ Luther, *Brit. J. Phot.*, 1910, 57, p. 664; G. I. Higson, *Phot. J.*, 1921, 61, p. 93-6.

transmitted by the two will be the resolved part of the OA vibration along the direction of OB'.

The amplitude of the resolved part transmitted = $OA \cos AOB'$ (where the vector OA represents by its length the amplitude of the vibration in that direction).

Part I of fig. 35 is intended to suggest the action of two Nicol prisms in stopping light when they are "crossed".

Very often in spectrophotometers it is arranged that the second prism receives two beams of light coming from two halves of the field in view, and it is generally arranged that the direction of vibration of the light in one half of the field shall be at right angles to that in the other half. Let the amplitude of the vibrations be represented in sign and magnitude by the vectors OA and OB (fig. 35, Part II). Then the final prism is turned so that it makes the apparent brightness of the two halves of the field of view equal.

This occurs evidently when

$$\begin{aligned} OA \cos AOB' &= OB \cos BOB' \\ &= OB \sin AOB'. \end{aligned}$$

$$\therefore \frac{OA}{OB} = \tan AOB'.$$

The intensity of a vibration being proportional to the square of its amplitude in every known case of wave motion, we put

$$\frac{I_1}{I_2} = \tan^2 AOB',$$

where I_1 and I_2 are proportional to the brightness of the two halves of the field of view of the instrument. *The control of brightness in this manner has also been compared with the results of distance variation, and is proved to hold exactly.*

There are certain precautions necessary with all these methods, but we shall discuss these in the section dealing with the different instruments.

Reactions of the Eye to Light.—The general subject of the reactions of the retina to light is one which is now receiving a great deal of attention. As has been previously stated, the power of adaptation of the retina and iris enables the eye to function *satisfactorily* even throughout a range of brightness of at least a million to one, although the range of brightness between day and night illumination is much greater. When light is cut off from the eyes the sensitiveness of the retina rapidly increases. If the original

state of adaptation was that resulting from a state of brightness

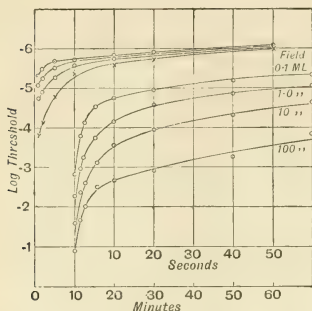


Fig. 36.—Dark Adaptation, White Light

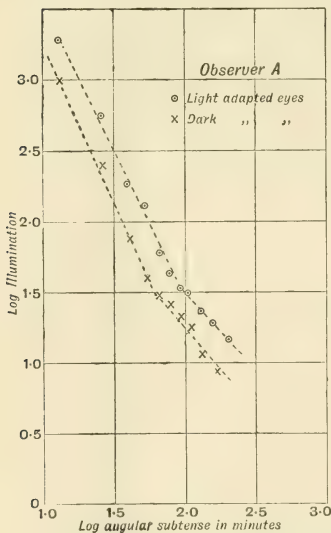


Fig. 37.—Threshold Illumination and Size of Stimulus Surface

approximating to indoor lighting during the day, the sensitiveness of the eye (measured by the reciprocal of the intensity of the least perceptible radiation) increases by a factor of something like 100,000 in three minutes, and continues to increase for at least one hour, the final factor being about 10^6 for white light. Fig. 36 shows the progression of dark adaptation with time from initial steady states of 0.1 to 100 milli-lamberts¹. For red, yellow, green, and blue light the factors are 10^4 , $10^{5.4}$, $10^{5.8}$, and $10^{6.2}$ respectively, but these are to be considered as approximate figures. For further details reference may be made to the original papers by Blanchard² and others. The present writer has investigated³ in some detail the effect of the size of the stimulus surface on the so-called "threshold" (minimum brightness perceptible to a dark-adapted eye), and it was found that the law $T \propto \frac{I}{a^n}$ is approximately true, where T is the threshold and a the angular subtense of the surface. When a is under about 1° the value of n is rather greater than 2, above 1° the value of n suddenly drops to 1 (see fig. 37).

¹ Milli-lambert, see Appendix.

² *Phys. Rev.*, 11, 81, 1918.

³ Department of Scientific and Industrial Research, Bulletin No. 3.

The yellow-covered fovea is less sensitive to light than the surrounding parts of the retina, and the above effects indicate that certain groups of the retinal elements are capable of acting in conjunction.

The minimum perceptible increase of brightness from a uniformly illuminated background, and the brightness necessary for efficient *form* vision follow very similar laws. It has been demonstrated that the maximum sensitiveness to contrast in a small illuminated field is not attained when the surrounding regions are absolutely black. By slightly lighting up picture theatres, the

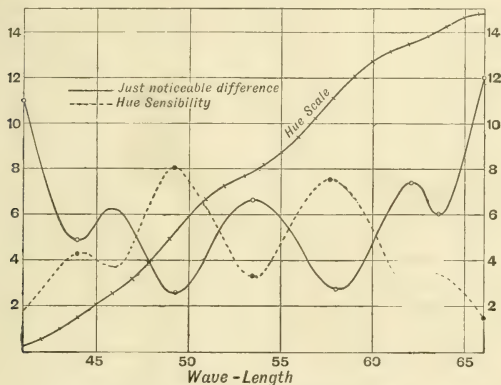


Fig. 38.—Hue "Limen", Sensibility and Scale

brightness of the picture required for comfortable vision is, if anything, a little decreased.

Hue "Limen".—A great deal of experimental work has been done in such connections as the measurement of the minimum variation in wave-length which will cause a perceptible difference of hue to the eye. A great deal of careful work has been done by Steindler,¹ and later by Jones and Nutting.² The success of the measurements depends almost entirely on the optical perfection of the apparatus by which the two contrasting fields in the comparison instrument are brought into contact. The general results are shown in the curve (fig. 38), which shows the variation of the "limen" (least *difference* of wave-length necessary to cause a perceptible change of hue) with the wave-length itself.

¹ *Wien. Sitz.*, 1906, IIa, 115, p. 1. ² *Jour. Opt. Soc. Amer.*, 1, 63, 1917.

A bright spectrum can in this way be divided into 120 to 180 steps, and the purples would give 20 different further gradations of *hue*.

Such steps of hue differences may be employed to give a "hue scale", which is somewhat different from the wave-length scale. Hue changes most rapidly with wave-length (as will be seen by the curve) in the blue-green ($\lambda = .490$) and the yellow ($\lambda = .585$). The most rapid variation in the relative ordinates of the "colour sensation curves" (to be described presently) is near these points, a circumstance which would naturally be expected whether the sensation curves have any physiological significance or not.

It is possible that such a "hue scale" would prove useful in the preparation of colour charts, &c., but otherwise it has little significance.

Tone Limen.—The corresponding "tone" limens or least perceptible steps in the "dilution" or "de-saturation" of a pure hue have also been investigated by Nutting and Jones.

Their data are given in the following table:

Percentage white	0	10	20	30	40	50	60	70	80	90	100
Percentage hue	100	90	80	70	60	50	40	30	20	10	0
Noticeable change in per- centage of white ..	4.7	4.6	4.5	4.4	4.2	4.0	3.7	3.4	3.0	2.5	2.1

These figures refer to the luminosity values of the light or the apparent brightness to the eye, and are said to hold for red, green, and blue light. The range of tone between a pure hue and black is dealt with under "CONTRAST SENSIBILITY".

Abney describes the results of a series of experiments to find the amount of a spectral colour which can be added to white light without being noticed, and concludes that if the spectral colour has a luminosity less than about $\frac{1}{10}$ of the luminosity of the white light its presence will be unrecognized. Aubert has conducted a similar inquiry with "colour discs", while Geissler has made a wider range of experiments in the same manner, working with red and grey of equal luminosity in the sectors of the disc. He finds about 90 perceptible steps between the "pure grey" and the "pure red", the increments being increases of grey sector angle of about 4° , and a corresponding decrease of red. Geissler also experimented with yellow, green, and blue papers. His values of sector "colour" apertures, giving just perceptible colour effect in

the prevailing grey for red, yellow, green, and blue, were 2° , 6° , 7° , 3° respectively. He considers the yellow and green papers relatively unsaturated colours.

It is difficult to reconcile the measurements on spectral colours with those using coloured substances, as sufficient data are generally lacking in the latter case. As we pointed out, however, in the first chapter, directly a range of saturations is obtained, the brightness of each member may be varied in a great number of steps to produce a wealth of "different coloured lights" (using the term colour in its broadest sense). Reference should be made to the discussion of contrast sensibility which follows.

As far as coloured substances are concerned, we shall do well to keep our ideas of *experimental* colour variations more on the following lines. We will imagine a white paper reflecting 100 per cent of white light, and a green paper of maximum apparent saturation reflecting up to 100 per cent of the green components of white light. A series of steps between the two will naturally involve both saturation and luminosity changes. We may imagine the steps produced by a rotating disc. Each step, however, represents the maximum possible reflection performance or *brilliance* for a particular state of saturation. If we had coloured papers corresponding to these steps we could then, by making sector discs of colour and black, secure a fresh series of shades from each step, all ending with black. Reeves states that there are about 700 shades of grey, but it will not be possible to secure so many shades from all the tint series, owing partly to the increasing hue saturation and the diminution of relative luminosity.

Experimental work with coloured substances is bound to be difficult, as the number of colours obtained depends so largely both on the spectral reflection coefficients of the substance and on the illuminant, as well as on the properties of the eye. Reeves comes to the conclusion that the number of distinct "colours" possible for material substances is probably not over 30,000. Such a vague conclusion illustrates the unsatisfactory nature of our knowledge of these subjects. The difficulty of experimental investigation must, however, be borne in mind.

Contrast Sensibility.—König and Brodhun have determined the "limen" of contrast for the eye, both for white light and for a range of wave-lengths. Their results agree, for moderate intensities of light at least, with Weber's law. This well-known generalization, which is applied to many other psychological phenomena, states

that the least perceptible increase of the stimulation of a sensation is a definite fraction of the intensity of the original stimulation.

Mathematically it would be stated thus:

$$\frac{ds}{s} = \text{constant} (= 0.016 \text{ approximately for light}).$$

This minimum value of the fraction holds very nearly for all colours, for moderate intensities.

Since the table is of great importance in connection with all photometric work, it is reproduced here. Intensities for the coloured lights are expressed as fractions of high, and apparently equal, intensities.

CONTRAST SENSIBILITY

Results of König and Brodhun

Wave-length.	·670	·605	·575	·505	·470	·430	White.
Field Brightness. ¹							
1,000,000							0.0358
500,000							0.0273
200,000		0.0425					0.0267
100,000		0.0241	0.0325				0.0195
50,000	0.0210	0.0255	0.0260				0.0173
20,000	0.0160	0.0183	0.0205	0.0195			0.0175
10,000	0.0156	0.0163	0.0179	0.0181			0.0176
5,000	0.0176	0.0158	0.0166	0.0160			0.0179
2,000	0.0165	0.0180	0.0180	0.0175	0.0180		0.0181
1,000	0.0169	0.0198	0.0185	0.0184	0.0167	0.0178	0.0178
500	0.0202	0.0214	0.0180	0.0194	0.0184	0.0214	0.0192
200	0.0220	0.0225	0.0225	0.0220	0.0215	0.0245	0.0222
100	0.0292	0.0278	0.0269	0.0244	0.0225	0.0246	0.0298
50	0.0376	0.0378	0.0320	0.0252	0.0250	0.0272	0.0324
20	0.0445	0.0460	0.0383	0.0295	0.0320	0.0345	0.0396
10	0.0655	0.0610	0.0582	0.0362	0.0372	0.0396	0.0477
5	0.0918	0.103	0.0888	0.0488	0.0464	0.0494	0.0593
2	0.1710	0.167	0.136	0.0655	0.0715	0.0600	0.0939
1	0.258	0.212	0.170	0.0804	0.0881	0.0740	0.123
0.5	0.376	0.276	0.208	0.0910	0.096	0.0966	
0.2		0.332	0.268	0.110	0.127	0.116	
0.1			0.396	0.133	0.138	0.137	
0.05				0.183	0.185	0.154	
0.02				0.251	0.209	0.223	
0.01				0.271	0.289	0.249	
0.005				0.325	0.300	0.312	
0.002						0.369	
Threshold ..	0.060	0.0056	0.0029	0.00017	0.00012	0.00012	0.00072

¹ Nutting states that the unit of brightness in this table corresponds to .004 milli-lamberts. For details regarding this unit of brightness see Appendix, Section 2. An illumination of 1 ft. candle on a perfectly reflecting and diffusing surface would give a surface brightness of 1.0761 milli-lamberts.

It should be explained that the field brightness is the mean brightness of the patches of light which reveal the contrast, and to which we may consider the eye is adapted.

1000 milli-lamberts or 1 "lambert" corresponds to an average outdoor brightness for objects in sunlight, while indoor brightness may be only one-thousandth part of this or 1 milli-lambert. Interior artificial lighting gives brightnesses of the order of 0.1 milli-lambert. From the table above it is seen that the field brightness to give best contrast sensibility is 2000 to 5000 units, corresponding to 8 and 20 milli-lamberts approximately. It is difficult, however, to keep up this brightness at the ends of the spectrum in spectrophotometry. Suggestions for a method of estimating the brightness of a photometer or colorimeter field will be found in the Appendix.

Purkinje Effect.—Referring to the table it will be noticed that luminosity matches might be made between red lights ($\cdot 67\mu$) or blue lights ($\cdot 47\mu$), both at a calculated field brightness corresponding to 10 units, but whereas the intensity of one red would have to be reduced by $\cdot 655$ units before the diminution in luminosity could be detected, the blue need only be reduced by $\cdot 396$ units.

It is found then, as might be expected, that equal red and blue brightnesses must be reduced by differing amounts to *keep* them apparently equal in intensity. If the reduction (produced by any photometric method) is equal, the blue will appear more luminous than the red.

It will be difficult at first for a beginner to realize how matches of equal brightness can be made between lights of differing colour or hue, but the answer that can be given is that the judging of brightness equality is a quickly acquired faculty, and, even though it is not at all easy at first, a surprising consistency in such matters is soon attained.

"True" Sensation Measurement.—As we shall discuss sensations in dealing with colour vision, we may with advantage pause to consider the method¹ by which the "amount of a sensation" may be derived if we wish to try and get a true sensation measurement, and not a mere measurement of stimulation.

First Step.—The contrast sensibility table for white light, say, is consulted, and the *actual differences* of brightness just perceptible or the amounts of the least increases perceptible are calculated from the values of the fraction.

Second Step.—The logarithms of the differences D are plotted

¹ Nutting, *Amer. Jour. Phys. Opt.*, April, 1920.

against those of the field brightness F . An evident linear relation between these logarithms leads to the law:

$$\log D = k + \frac{2}{3} (\log F), \text{ where } k \text{ is a constant,}$$

$$\text{or } D = KF^{\frac{2}{3}}, K \text{ being another constant.}$$

The difference of sensation δS caused by a difference of brightness δF is assumed to be proportional to $\delta F/D$,

$$\text{therefore let } \delta S = \frac{F^{-\frac{2}{3}} \delta F}{K}.$$

As we may choose any units to measure S , the sensation, let us put $\delta S/\delta F = 1$ at the threshold when $F = F_0$.

$$\text{Then we have } \frac{1}{K} F_0^{-\frac{2}{3}} = 1.$$

$$\therefore \delta S = \left(\frac{F}{F_0} \right)^{-\frac{2}{3}} \delta F.$$

Third Step.—Integrating between the limits F_0 and F we find

$$S = 3F_0^{\frac{2}{3}}(F^{\frac{1}{3}} - F_0^{\frac{1}{3}}).$$

Therefore the “sensation” is proportional to the cube root of the brightness of the field except for low intensities. We are not to confuse this theoretically derived sensation intensity with the term “sensation brightness”, for we have seen that the sensation brightness will merely refer to energy, or amount of stimulation. In our present state of knowledge it is hardly clear whether this so-called “true” sensation value has any physical significance.

Effect of Dispersion on the Distribution of Energy in the Spectrum.—Experimental work has abundantly confirmed the theoretical deduction that the distribution of actual energy in the spectrum of a definite and unchanging radiation is rigidly connected with wave-length. Thus, for example, if half the energy in the spectrum of a given source is found between two particular wave-lengths, this will always be the case no matter what dispersing system is employed, provided that we neglect possible absorption effects of glass or the like, in the optical system. With differing dispersing systems, however, it is found in studying their characteristic spectra that the relation of wave-length change to linear displacement in the spectrum is by no means the same.

With prism spectroscopes the dispersion is relatively low at the

red end, but with gratings linear displacement in the spectrum is more nearly proportional to the wave-length.¹ The energy in a given region of the spectrum of a constant source is evidently inversely proportional to the dispersion.

Variation of Luminosity in the Spectrum ("Flicker" Photometer Methods).—As was previously indicated, the relative luminosity of different parts of the spectrum depends on the eye (the part of the retina used), the nature of the source, and the type of dispersion. These must be kept constant in any series of measurements. We can, however, use them, if known, to obtain data on *spectral visibility* (that is, the quotient of the luminosity by the energy) at each point of the spectrum. This has been done by a number of observers. The *energy* is calculated from the dispersive properties of the prisms, or may be found directly by a thermopile or bolometer in the spectrum.

As well as the method of direct photometric comparison with white it is possible to use a flicker method for determining the luminosity values. In the apparatus used by Watson a simple rotatory apparatus ensures that a single screen is lit alternately (about ten times per second each) by the white and the coloured beam. A calibrated wedge or annulus is most convenient to control the intensity of the one of them which is varied until the flicker vanishes. The same part of the retina must be used for each observation.

Luminosities found in this manner differ slightly in degree from those found by the direct method, agreeing fairly well for the wave-lengths shorter than that of the brightest light in the spectrum, but falling below the luminosity found by the ordinary shadow method for longer wave-lengths (Ives).² To convert "flicker" luminosities to "shadow" luminosities, Watson multiplied the flicker values by a constant, but later work showed this to be unnecessary.

Another method of measuring spectrum luminosities employs a critical flicker frequency method. This is fully described in the chapter on colour vision, under the subject of colour fatigue. In this case the coloured light is alternated with darkness, and the speed at which flicker vanishes is found. The frequency has a linear relation with the logarithm of the sensation brightness (see fig. 61).

¹ The wave-length bears a linear relation to the sine of the angle of diffraction.

² *Introduction to the Study of Colour Vision*, p. 99.

Owing to the Purkinje effect (pp. 62 and 91) the luminosity curve changes very considerably with the absolute intensity of the spectrum. The point of maximum apparent luminosity shifts considerably towards the shorter wave-lengths with decreasing intensity.

Some considerable discrepancy exists between the results of various observers for visibility. Nutting and Ives have used the critical frequency method. Nutting measured the energy distri-

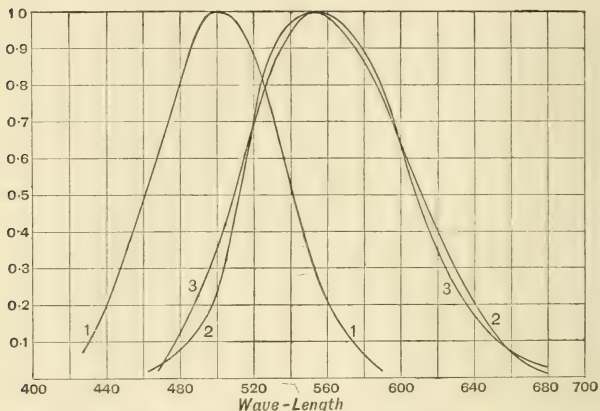


Fig. 39.—Visibility of Radiation and Purkinje Effect

1, König's results (low intensity). 2, Abney and Watson (higher intensity).
3, I.E.S. (America), mean result.

bution and Ives calculated it. König has given results for low intensities which have been recalculated by Nutting. Some of these results are given in the diagram (fig. 39). The curves 2 and 3 are those given, for central vision with reasonable intensities of light by Abney and Watson and by Nutting respectively. Curve 1 shows the class of results obtained at much lower intensities and is similar to König's curve. Abney and Watson¹ suggest that since they employed a very small photometric field their results are confined to images on the fovea (pure *cone* vision), while other observers using a larger field give results for mixed rod and cone vision. Since it is easier to see very faint lights away from the

¹ *Phil. Trans. Roy. Soc., A.*, Vol. 216, p. 123.

fovea, König's results probably refer to *rod* vision. The ordinates of the curves have all been altered to make the maxima equal to 1, as their proper relative values are not specified.

Threshold of Vision for Different Coloured Lights.—In making experiments on the Purkinje effect it is necessary to keep very carefully to the one particular part of the retina used for observation. Fig. 40 shows curves due to the late Professor Watson, connecting logarithms of energy at the threshold of vision with wave-length expressed in terms of Abney's Spectrum Scale. The experiments were made using parts of the retina at varying angular distances from the fovea, the curve labelled 0° being taken at the fovea itself. It is at once seen that in this case the fovea is (except for the extreme red) the most insensitive part of the retina, and that the sensitiveness increases to a maximum at about 5° from this point. Hue can be appreciated at the foveal threshold of vision, but in the outer parts of the retina the beginnings of the light sensation are colourless no matter what wave-length of stimulating light is employed. The curves in fig. 40 are roughly the inverse of the "luminosity" curves, and should be considered in connection with what has been said as to the yellow pigmentation of the macula.

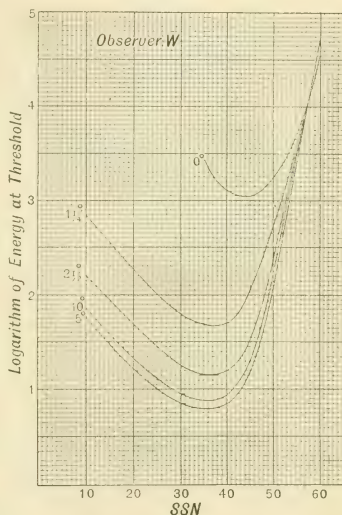


Fig. 40.—Curves showing Relation between Wave-length and Threshold of Vision

CHAPTER VIII

Instruments for Colour Measurement

The general purposes of various instruments employed in colour measurements have already been discussed in Chapter III. Their construction and method of use must now be discussed in greater detail.

The Colour-patch Apparatus.—This was designed and elaborated by Abney and was used by him in many of his researches.

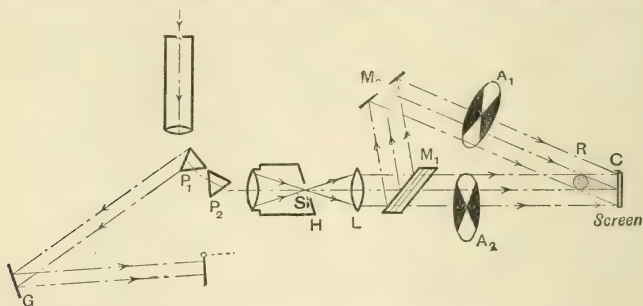


Fig. 41.—Colour-patch Apparatus (Diagrammatic)

P_1 and P_2 , The prisms. H , The spectrum. A_1 and A_2 , Lummer-Brodhun sectors.
 G , Mirror for obtaining a comparison white light on the screen.

It is equally available and useful for spectrophotometric work and for investigations in colour vision. Reference may be made to fig. 41 for a general diagram. The essential part of the instrument is seen to be the (now familiar) arrangement for forming a spectrum. The use of an achromatic lens of fairly long focal length brings the spectrum to a focus (sufficiently nearly) in the plane of a slide H , which carries one or more slits S , the widths of which are adjustable by micrometer screws. When narrow these slits emit spectral light, which may (for practical purposes) be assumed monochromatic.

The large lens L is of such a power as to form an image of the first prism face on the screen C; thus uniting all the radiations which are dispersed in the plane of the spectrum, provided no obstructions are present. If, however, the slide is in position with only one slit open, the screen will receive an image of the prism face formed in monochromatic light, the wave-length of which is determined by the position of the slit S relatively to the spectrum. Two or more wave-lengths may obviously be mixed in this way by the use of a corresponding number of slits.

For comparisons of coloured light with white a beam *reflected* from the first prism face is employed, and can be directed towards the screen by the use of a mirror G. If a rod R is placed in a suitable position it will throw two shadows,¹ one due to the white light, and one due to the coloured light from the slits. Each shadow is evidently illuminated only by light from the other source, the apparatus being used of course in a darkened room.

In practice the screen consists of a rectangular piece of brass about 1.5×3 cm. and coated with the smoke from burning magnesium ribbon. This is mounted on a small block covered with black velvet, and the block itself stands against a background of black velvet also. The "touching line" of the two shadows bisects this small screen, and a very satisfactory photometric field is thus obtained. Direct measurements of spectrum luminosities can be carried out with this arrangement if means are available to control the brightness of the beams. We shall return to this topic.

The instrument is slightly modified in order to use it as a spectrophotometer, the white beam being no longer employed. Fig. 41 will illustrate the arrangement. S is the slit moving in the spectrum, and L the lens which throws an image of the first prism face on the screen. A glass plate or bundle of plates M_1 reflects a part of the beam to the second mirror M_2 , whence it comes back to the screen. As before, the rod R is arranged to give the two shadows, and, for transmission measurements at least, the white screen is still employed. If it is desired to measure percentage *reflection* coefficients of a surface (as compared with white) the screen is made up of two parts, one of which is the standard white, and the other part is composed of the material under test. The two shadows touch along the separating line of white and colour. An all-white screen is also necessary for preliminary work.

¹ In fig. 41 the position of the rod is not correct for this type of work, in which the mirrors M_1 , M_2 would be omitted.

Lummer-Brodhun adjustable sectors are used in one or both beams to control and equalize the intensities of the two halves of the field. Let the original intensities of the two beams be A and M (auxiliary and main beams), and let S_A and S_M be the apertures in degrees of the sectors in the auxiliary and main beams respectively when the intensities on the all-white screen are equalized.

$$\text{Then evidently } AS_A = MS_M.$$

It is important to calibrate the beams against each other through the whole spectrum.

If then we desire to measure the transmission coefficients of a filter it will be held in the path of the main beam, or alternatively if it is desired to investigate the reflection coefficients of a surface, a patch of this must be placed so that it is illuminated by the main beam immediately against a patch of white illuminated by the auxiliary.

It will in general be necessary to readjust the sectors in order to secure equality of brightness in the photometric field. Let S'_A and S'_M be the final apertures when a specimen with transmission or reflection coefficient K has been placed in the main beam, then

$$\begin{aligned} S'_A A &= S'_M KM. \\ \therefore K &= \frac{S'_A A}{S'_M M} \\ &= \frac{S'_A S_M}{S'_M S_A}. \end{aligned}$$

In case no sector is used, the aperture would be treated as 360° . In the latter case we assume the reflection coefficient of the white to be 100 per cent—but if it is not, or if any selective effects are present, a correction will be needed. The experimental investigation of the *absolute* reflection coefficients of diffusing surfaces is somewhat difficult experimentally, and little information is at present available (see Appendix).

Diffraction Gratings.—Reference to the diffraction grating was made in a previous chapter. This is constructed in the first place by ruling a great number of fine “lines” very close together on a glass plate or speculum mirror. As many as 60,000 to the inch may be drawn by the use of a special engine actuating the ruling diamond. A section of the surface *if highly magnified* would appear to possess a serrated edge, as suggested in fig. 42. “Casts” of such

gratings are made in celluloid, and when mounted on glass serve almost equally well. Gratings in ordinary use possess generally about 14,000 lines per inch. When a distant source of light is viewed through such a transparent grating, two or more spectra are seen on either side of the direct image, the separation and dispersion increasing with the number of lines per unit length. In order to adapt this device for use in a *direct-vision* spectroscope a prism may be used (in place of the compound prism in fig. 18), which not only brings one of the spectra into the direct line of sight but also increases the dispersion obtained. The ordinary undiffracted image is deviated by the prism in accordance with the laws of refraction (see fig. 43).



Fig. 42.—Section of Surface of Diffraction Grating (highly magnified)

Spectrophotometers.—Nutting has designed a convenient spectrophotometric apparatus which is employed in conjunction with an ordinary spectrometer. It is illustrated in fig. 44. If we wish to compare intensities throughout the spectra of two sources

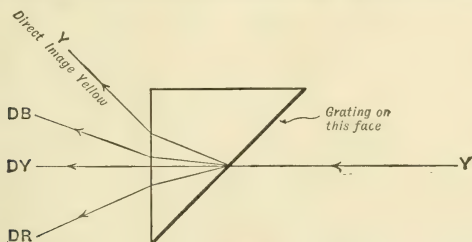


Fig. 43.—Shows Action of Prism with a Grating in a Direct-vision Spectroscope

DB, Diffracted blue. DY, Diffracted yellow (seen direct). DR, Diffracted red.

of light, we arrange so that light from them is thrown into the apertures shown; that from P is reflected at the 45° surface of the first prism and then sent towards the slit S of the spectrometer, while the light from Q passes through the Glan-Thompson prism G_1 , and is reflected at the interior face AB of the compound prism. This face AB is silvered in strips at right angles to the direction of the slit, and the lens L projects an image of the strips on the slit through the analysing prism G_2 . The result of this is that we have successive short lengths of the slit illuminated alternately by the two

sources, and the spectrum is divided into bands illuminated alternately in the same way.

Now the intensity of the light from Q is controlled by the relative angular positions of the polarizing prisms, so that we have a means of equalizing intensity and thus measuring the *relative* intensities of the illumination on the face AB, due to the two sources, in any part of the spectrum. The angular position of G_2 is indicated by a divided circle and pointer.

The law of the variation of the intensity of the light from Q will be $I_1 = I_0 \cos^2 d$, where I_0 is the maximum intensity and d is the angular deviation of the prism G_2 from the position of maximum brightness. The light from P suffers no alteration in brightness.

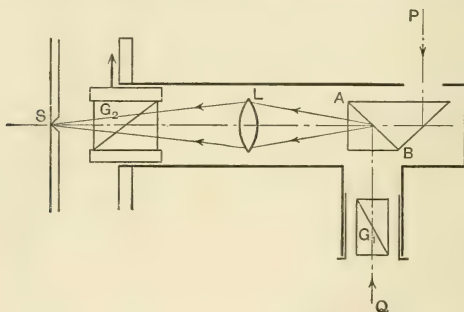


Fig. 44.—The Nutting Spectrophotometric Attachment for a Spectroscope

A convenient form of this apparatus is made up by Messrs. A. Hilger, Ltd. It is arranged in a slightly different form, so that the same source may illuminate both apertures, when the instrument may be employed to measure the absorption of dyes, glass, &c. A "density" scale is also provided (see p. III).

König-Martens Photometer and Spectrophotometer.—

Instruments of this type are now being used not only for the measurement of transmissions, but also (in conjunction with a special "integrating" device) for the measurement of diffuse reflection coefficients.¹ It will be as well to describe the optical system in two steps, and we will take first the photometer system, illustrated in fig. 45a, which is a well-known one employed in pyrometers.

A and B are two apertures which receive light from the two

¹ See Appendix.

sources to be compared. We may take it that a beam diverges from each of these apertures, and meets the lens C, which then produces two collimated beams making a definite angle with each other.

The next part of the system is the "double image" prism D. A complete description of the construction of this may be found in textbooks on light, but it will suffice to say that a single beam of light passing through such a prism is split into two parts which diverge from each other, the two parts being polarized in perpendicular planes. In our photometer the two collimated beams from C thus become converted into *four* polarized beams.

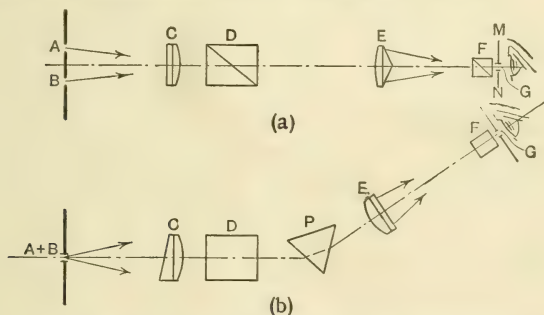


Fig. 45.—König-Martens Spectrophotometer, Optical System (diagrammatic)

The light next meets the combination of lens and "biprism" E. The lens portion of this would suffice to bring the four collimated beams to a focus in the plane MN, in which case four images would be found, but the biprism produces a further split in each beam, thus making eight in all.

Of the eight images found in the plane MN, however, only two are of importance, and these are brought to focus *together on the axis*. One is from each aperture, and the two are formed by light polarized in perpendicular planes. Again, the light forming one image is derived from the top portion of the biprism (in the diagram), while the light forming the other is derived from the lower portion. A small aperture G allows this light from the central images to pass through, the light from the remaining six images being stopped. The beams, before reaching the aperture, traverse a Nicol or Glan-Thompson prism F, which is used as an "analyser".

An eye observing through G now sees the two parts of the biprism illuminated by light from the two apertures respectively. The conditions necessary for comparison described in the chapter on photometry (p. 81) are also fulfilled, and we may compare the relative intensities of the sources from a knowledge of the relative angular position of the analyser when a match is made. The analysing prism is mounted with pointer and divided circle as usual. The instrument as it stands is thus an extremely useful one for illumination photometry, and other purposes.

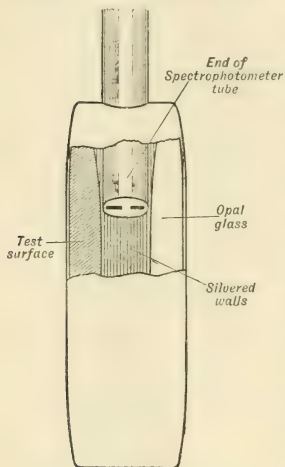


Fig. 46.—Integrating Cylinder

In order to convert the system into a spectrophotometer a dispersing prism must be added, which necessarily produces the dispersion in a plane perpendicular to that of the diagram in fig. 45*a*. Fig. 45*b* shows a vertical section of the instrument. The 60° prism P produces an upward deviation, and as the width of the apertures is small in a vertical direction, the small aperture G will only transmit light from a very small range of wave-length in the spectrum. The small prism cemented to the lens C is for the purpose of deviating some stray back-reflected light out of the path of the main beams. The pieces E, F, and G are mounted in a tube, which moves in a vertical

plane about a horizontal axis in the neighbourhood of the prism, and its position is controlled by a micrometer screw with a graduated drumhead. The selection of any special region of wave-length is thus made easy. The spectrophotometer may be employed directly for measurements of the transmission coefficients of light filters and the like.

Integrating Cylinder.—Measurement of the reflecting coefficients of surfaces throughout the spectrum may be carried out with this apparatus in the following manner. A shallow cylindrical drum (fig. 46) has one of its interior flat faces coated with the test surface, while the other flat face is composed of some translucent substance, such as white opal glass, as non-selective as possible.

The interior of the cylindrical ring separating these faces is silvered and polished, the effect being to illuminate the test surface *almost uniformly from all directions*. The two apertures of the instrument then receive light diffused from the two flat surfaces, and a direct measurement of the reflection coefficient is thus made. Small prisms may be used in front of the two apertures to introduce the light from the surfaces at the correct angle. The limitation imposed by the conditions of illumination must be borne in mind when considering the results, especially if the surface is not quite "matt". This arrangement is now stated to give results uniformly too low. (See Appendix.)

Other forms of spectrophotometer are in use, but their general principles generally follow the lines of those already described. We must now proceed to the description of instruments which are intended to measure the appearances of coloured light or objects.

Photometric Comparison Cube.—This useful piece of apparatus was originally invented in 1859 by Swan, but in its modern and improved form it is usually known as the Lummer-Brodhun cube. It is illustrated in figs. 47, 48, and 52, and may be explained as follows. A complete cube of glass could obviously be constructed by cementing together the hypotenuse faces of two equal right-angled prisms. If the outer part of the hypotenuse face of one prism is removed by a shallow "spherical" grinding tool, a centre circular portion of the face will remain polished. The circular portion is cemented to the first prism as before. The net result of this is that light is reflected when incident beyond the critical angle at 45° or so on those parts of the "all flat" prism surface which are not in contact with the centre of the other prism, but rays incident on the cemented part of the contact surface are freely transmitted. In some cases the flat separating faces are now silvered in parts instead of one being ground. This produces much the same effect. It is a great advantage in photometric and colorimetric matching to use such a field that the light from one source may be seen on two sides of the central patch which is illuminated by the other source. This condition tends to prevent errors due to visual fatigue, as the match must be made perfect on the two dividing lines. Referring to fig. 52 (the Arons colorimeter), it will be understood that the eye viewing the separating surface in the cube C sees the outer portions illuminated solely by light which has entered the cube in a downwards direction and has been reflected, while the centre is illuminated solely by the freely

transmitted light coming in horizontally. This arrangement forms a component part of several types of colorimeter, and it has been thought best to describe it separately before proceeding to the discussion of particular instruments in which it appears.

Nutting's Colorimeter.¹—The diagram (fig. 47) shows a sketch of the general arrangements of the original instrument, and the details of the complete apparatus, as made up by A. Hilger, Ltd., are shown in fig. 48. In its original form the apparatus consisted

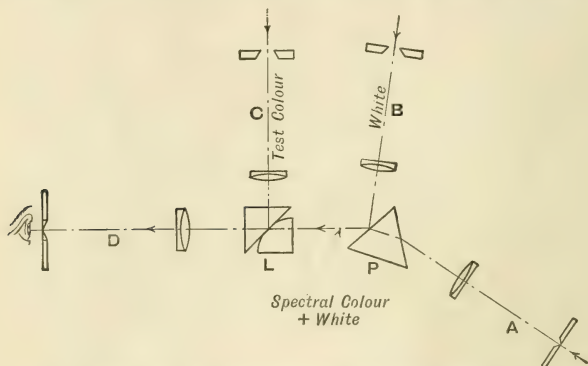


Fig. 47.—Nutting Monochromatic Colorimeter (original form). The apparatus for varying the relative intensities is not shown

mainly of a spectroscope with the collimator A, the prism P, and the telescope D from which the eyepiece is omitted and replaced by a slit.

If the Lummer-Brodhun prism L were absent, an eye placed at D would see the prism P illuminated by monochromatic light.

A beam of white light can be introduced by the collimator B, this light being reflected from the prism surface and taking the same path as the first beam. The remaining part of the apparatus is the Lummer-Brodhun comparison prism L, and a third collimator C, which receives the light for comparison. The eye views the separating surface in the cube, and the field of view is thus divided sharply into portions lit by the "test light" and the mixture of white and monochromatic light respectively. The relative brightnesses of the beams may be controlled by alteration of slit

¹ See *Bull. Bureau of Standards*, 9, 1913, pp. 1-5; *Physical Review*, 4, 2nd series, pp. 454-66.

widths, sectors, wedges, polarizing prisms, or any other convenient method. The instrument deals directly with transmitted light of

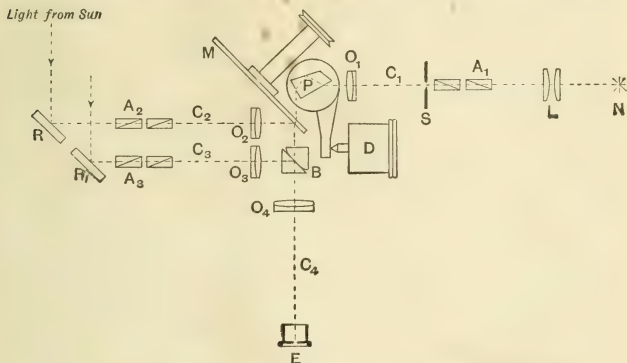


Fig. 48.—Nutting Colorimeter, Hilger Diagram

any colour except such hues as purple. In order to deal with purples which cannot be matched, it is necessary to employ another

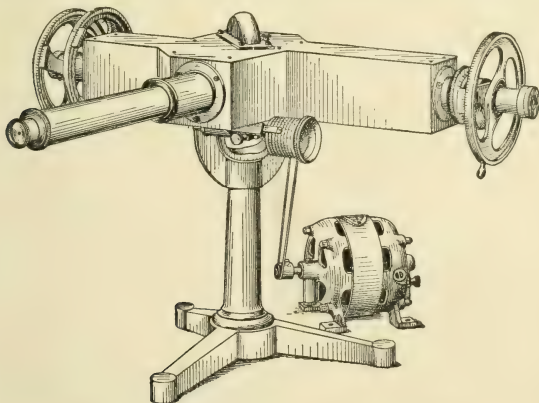


Fig. 49.—Nutting Colorimeter, General View of Apparatus

arrangement by which a known intensity of some spectral colour is mixed with the purple to form a white, the hue thus being ex-

pressed in terms of its complementary. In this case the functions of collimators B and C are interchanged.

In the later and more complicated form (see also fig. 49) a Hilger spectroscope is employed, in which wave-lengths may be read off on the drum D by means of which the dispersing prism is rotated. Pairs of Glan-Thompson prisms are employed to vary the intensities of light in each of the three collimators. M is a sectored mirror, which either rotates at high speeds to mix the white light, from the collimator C, with the spectral colour, or can be used to determine the relative brightness of white and spectral colour by the well-known "flicker" method, in which the mirror is made to rotate at about 120 revolutions per minute, and the intensity of the white is adjusted till flicker disappears, when the two intensities are taken to be nearly equal. A small correction can be applied if desired to reduce "flicker luminosities" to the ordinary matching luminosities of spectral colours, but this will generally be unnecessary (see p. 93).

If it is desired to investigate the colour of a material substance, it is, if opaque, placed outside the opening of the collimator C_3 and illuminated by sunlight, or, if transparent, sunlight is reflected from the white blocks R and R_1 and may pass through it, arranged as a light filter, into C_3 .

The eye behind the aperture E sees the different parts of the Lummer-Brodhun cube illuminated by light from the parts of the objects which occupy the foci conjugate to E, formed by the lenses O_2 and O_3 with O_4 and the different reflecting arrangements. If a purple is to be tested, the arrangements outside the collimators C_2 and C_3 are interchanged.

A steady source M is used for the production of the spectrum, and this may be a "Point o' lite" lamp, a half-watt type lamp, or the like, but daylight or artificial daylight is necessary for illuminating the collimators C_2 and C_3 . Unless a great sensitiveness and accuracy is required (which can hardly be attained with the apparatus) ordinary daylight (light reflected from white clouds, &c.) will be found to be of sufficient constancy, unless there is a tendency to yellow fog, &c. Direct sunlight is desirable for its intensity. (See further notes in the Appendix.) When using the Nutting colorimeter, or similar apparatus, the dominant hue is obtained by direct measurement, and it also gives the proportion of spectral *light* to white *light* in the matching colour. We can also obtain directly the brilliance of the test object as compared with white.

This gives everything required for the ordinary colour notation.

It may be necessary, however, to distinguish between the proportion of pure hue *sensation* and the proportion of pure spectral light. If we desire to express saturation in terms of sensation (which is probably the only really satisfactory way from the scientific point of view) the amount of white sensation luminosity, if any, in the spectral light must be found from the tables (see the next chapter) and the results corrected.

Colorimeters depending on Three-colour Mixture.—

Instead of deriving the primary colours from the spectrum, we may produce three arbitrary primaries by colour filters of red, green, and blue glass (or gelatine¹). The apparatus is arranged so that light passing through three such filters may be varied in intensity and finally mixed. The field of view should secure a sharp division between the portions illuminated by the light to be matched and the composite light.

This is the condition most important for accuracy of observations. Where strictly monochromatic light is used for the primaries, some little difficulty may be met with on account of the chromatic aberration of the eye, as the monochromatic patches subtend different angles on the retina and give the patch an appearance of coloured edges. This will be less noticeable when filters are employed, as each will transmit a range of the spectrum, and the borders to the coloured edges will be noticeably less marked.

Three-colour measurements of this type may be made very conveniently on the colour-patch apparatus.

An alternative is offered by the rotating-disc method, as previously suggested. If the colours are chosen extremely carefully, and if the lighting and contrasting of the test surface with the disc surface is arranged with great care (using optical devices if necessary) so as to resemble an ordinary photometer field of view, it is possible to make very accurate measures. A little experimenting, however, will soon show that it is extremely difficult to match some of the more saturated colours, such as yellow, because of the amount of white in the light from the discs. The accuracy of the determination of the amounts of the components may be brought to within 5 per cent.

Ives Colorimeter.—This instrument (recently introduced in America) also depends on the use of three-colour synthesis. The primaries consist of lights from three slits provided with red, green,

¹ Dyed gelatine filters are apt to fade.

and blue filters, the relative intensities being controlled by the apertures of the slits. The mixing is performed by a wheel of rotating lenses which illuminate one-half of the photometer field, the general effect being secured by persistence of vision and the consequent integrating power of the eye. The instrument appears to be convenient for its original purpose (analysing the colour of illuminants) or for determining the properties of light-filters and coloured material substances which can be illuminated sufficiently brightly.

The probable error of determination of the amount of a component is said to be of the order of 2 to 5 per cent, which is just sufficiently good to make the instrument of practical use. One great merit is the production of a sharp boundary line in the matching field by the use of the small prism, which brings the light from the unknown source to the eye.

When a trichromatic colorimeter is employed for analysis or synthesis, the power of assigning to a colour its true place in the colour triangle (i.e. determining from the indications of the instrument the colour sensation in terms of its true red, green, and violet components) must obviously be completely dependent on an accurate knowledge of the sensation values of the lights transmitted by the three primary filters in that instrument.

These must therefore be examined with great care, before mounting, by some accurate spectrophotometric method. The sensation values are then calculated, and it will be possible to link up the indications of the colorimeter with the hues of definite wavelengths. Naturally, in order to correlate the indications of many different instruments, it is necessary to have accurate sensation curves. The procedure is outlined by Ives¹, who used his trichromatic colorimeter for analysing the light from a number of illuminants. A method due to Abney is outlined in the next chapter.

Similar methods, of course, can be used for linking the indications even of instruments operating on subtractive principles, with the ordinary hue, saturation, and brightness notation.

The Bawtree Colourmeter.—This instrument has recently been introduced in Great Britain (fig. 50), and employs an arbitrary scale of colour based on the additive principle. The instrument consists of two light-diffusing systems, which may be illuminated by artificial light, or by daylight and artificial light

¹ *Trans. I. E. S. (America)*, 1910, p. 189.

respectively. The matching field consists of two areas about 2 in. square. Light diffused from the test surface H illuminates one of the areas, its intensity being controlled by a shutter actuated by a micrometer screw. The other area is illuminated by light passing through three adjustable shutters screened respectively by scarlet, green, and violet gelatine filters. A white light is obtained by opening all three of these shutters almost to their greatest extent. Various hues are obtained according to the relative apertures of the shutters (indicated by the pointers E, F, and G in fig. 50), and the readings of these thus furnish an arbitrary scale of colour.

The colour of a material may thus be "measured" when it is illuminated by artificial light or daylight.

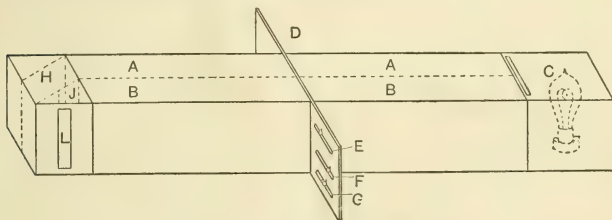


Fig. 50.—The Bawtree Colorimeter

Some limitations of the method will be clear from the considerations appearing elsewhere in this chapter, but, as far as can be judged, the instrument is not yet perfected. It has the great merit of simplicity. In order to obviate the difficulty of matching fully saturated yellows a fourth (yellow) screen is introduced in some instruments.¹

In addition to the difficulty of matching saturated yellows there are also difficulties in matching other fully saturated colours with hues near that of the red filter. The hues can be matched, but not at full saturation. Difficulties of this kind are, however, common to all colorimeters working on the additive principle, and those working on the subtractive principle are by no means immune.

Bawtree has worked out a scheme² for expressing results derived from his instrument in terms of hue, purity, and brilliance. To illustrate it we may take a colour which is matched by, say, 70 blue, 30 green, 40 red. Since the instrument is graduated so that equal parts of blue, green, and red make white, this is equivalent to 40

¹ In some instruments the colour mixing and diffusion is not yet satisfactory.

² *Journal of Oil and Colour Chemists Association*, November, 1921.

blue, 10 red, and 30 white. The hue is thus found as that corresponding to a point dividing the blue-red side of the colour triangle in the ratio of 40 to 10. A circular scale of hue is imagined to circumscribe the triangle, and the radius through the above point fixes the hue on this arbitrary scale. In a further development a special form of colour cylinder is imagined in which the axis runs between black and white. The "intensity" of the pure hue component is defined as "equal to that of the largest remaining component after the white has been subtracted"; for example, in the above case the intensity would be taken as 40. It will be seen that this does not correspond directly to luminous intensity, so that, although a colour notation with the special meanings of purity and

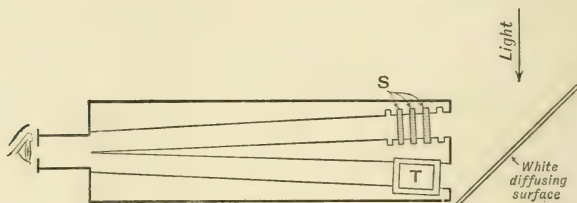


Fig. 51.—Tintometer (diagrammatic)

T, Cell for holding liquid. S, Slots for holding coloured glasses.

brilliance adopted in the present case *might* be employed with success, it will be somewhat different from that which has been discussed in the first chapter of the present book. If necessary the sensation values for the filters could be evaluated in a manner similar to that used by Ives. It is not necessary to employ Bawtree's special notation in order to use the instrument for colour measurement. (*Experientia docet.*)

Colorimeters depending on Subtractive Mixture.—In producing colour variations by subtractive colour mixture the light has often to pass in succession through three colour filters; it is not possible to introduce variations of hue and saturation by mechanical changes of aperture, as in the additive mixture instrument, but it can be done by changing the thickness of liquid filters.

The Tintometer.—In the "tintometer" method of colour measurement a set of glass colour filters with differing saturations of the subtractive primaries (crimson, yellow-green, and blue, making 470 glasses in all for a complete colour matching set) are supplied.

These glasses are numbered in a scale which expresses "depth of colour", and the steps are so adjusted that equal numbers in the three colours produce greys. Any colour is thus expressed as x purple, y yellow, z blue. The "optical instrument" supplied (fig. 51 represents an early form) is simply a viewing box in which two apertures are illuminated, one by light passing from a white plate through the standard filters, the other by light coming from a reflector of which the colour is being examined, or through a cell of liquid, &c.

The apertures are separated in the earlier instruments. This is a feature which tends to prejudice accuracy of matching, but simple optical means are available to bring the fields together.

Special sets of filters are supplied for different purposes where a limited range of colour is to be examined.

Undoubtedly the resulting system of colour notation (though arbitrary) is very definite. The apparatus has two great merits: great simplicity, and the avoidance of all elaborate measurements and calculations. In addition the glass filters will be quite permanent. Thus the only precaution necessary in using the scales for colour standards is to control the colour of the light employed. According to the directions issued by the company, this light must be diffused light from a north window, and it is recommended that special diffusing screens shall be employed. Care in this connection is important, as the grey combinations of equal scale numbers have a somewhat high transmission in the extreme red. It is therefore important to employ light which does not contain any excess of red.

Every set of glasses issued has to pass an elaborate series of tests, and the accuracy of the reproduction of the laboratory standards appears to be high. There can be no question that the perfectly steady and uniform matching fields which the method employs offer the best conditions to the eye, and, furthermore, since no optical dispersing system has to be employed, no great intensity of light is called for.

Some particulars of tests on the scales are given by Lowry and M'Hatton¹ who point out that the *densities* of the standards should be proportional to the scale numbers.

The *density* of a light filter is defined as the logarithm of the *opacity* where

$$\text{opacity} = \frac{\text{incident light}}{\text{transmitted light}}.$$

¹ *Journal of Oil and Colour Chemists Association*, No. 27, Nov., 1921, Vol. IV.

If there be three light filters of opacities O_1 , O_2 , and O_3 which are placed together so that the light is traversed by each in turn, the final value of the fraction

$$\frac{\text{light incident on first filter}}{\text{light emergent from last filter}} = O_1 \times O_2 \times O_3 = \text{combined opacity.}$$

Taking logarithms, it is seen at once that

$$\log O_1 + \log O_2 + \log O_3 = \log (\text{combined opacity}).$$

Therefore, if the scale numbers S_1 , S_2 , and S_3 of the filters are proportional to the densities, the scale number corresponding to the effect of the three in series will be $S_1 + S_2 + S_3$.

Not only will the densities of the coloured standards follow this law, but the densities of the grey series, made by taking equal scale numbers of the three subtractive primaries, will follow it also.

Lowry and M'Hatton give a curve showing that a linear law is obeyed within small limits of error, more especially for the scale numbers above 3. The law appears to be somewhat different between 0 and 3.

In making matches with low scale numbers it is advisable to compensate for the light reflected from the surfaces of the slips by using an equivalent number of plain glasses in the beam from the test substance. This will generally permit an exact match in intensity as well as in hue. The scale ranges from 0.01 up to 20 in each colour, the smallest number corresponding to a colour difference only just perceptible to the eye when introduced into white.

As was previously indicated, the great value of a set of this kind is for colour standardization rather than for measurement in terms of physical or other fundamental units; and for standardization purposes the accurate reproduction of the scales (rather than the law they follow) is the main consideration. We are at present a very long way from the perfect method of measurement, but much nearer the possibility of consistent and exact standardization. The discrimination between the extremely unsaturated colours found for example in different varieties of "white" paper and the like calls for extremely delicate variations in a comparison field. The Tintometer scales are, however, being used with success in cases of this kind. As in the additive instruments, difficulties are found in matching directly some of the more highly luminous and fully saturated colours with hues intermediate between the primaries, and special methods must then be employed.

Jones's Colorimeter.—L. A. Jones¹ has recently described a new form of colorimeter employing the subtractive principle of colour mixture. Instead of the series of glasses, as used in the tintometer, gelatine *wedges* of blue-green, yellow, and magenta (together with a neutral wedge for controlling intensities) may be used to modify the light received in one part of the photometric field of the instrument from a standard source. This standard consists of a small electric lamp (run under standardized conditions), the light from which is transmitted through a filter to correct the quality of the light to that of daylight or noon sunlight. An image of the object of which the colour is to be measured illuminates the other part of the photometric field. A standard lamp (not

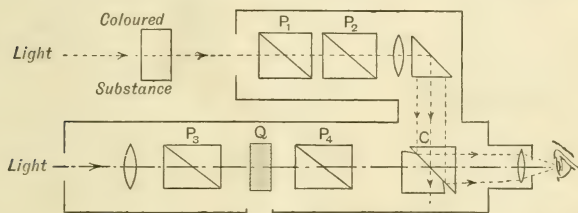


Fig. 52.—Arons' Colorimeter (diagrammatic)

P_1, P_2, P_3, P_4 , Pairs of polarizing prisms controlling intensities of light. Q , Quartz plate. (A variety of these, having different thicknesses, is provided; they may easily be interchanged.) C , Lummer-Brodhun Comparison Cube.

electric) is also provided with a suitable filter for standardizing the white from the electric lamp from time to time.

By means of methods which have been indicated, the wedge scale readings to match any colour may be interpreted in terms of hue, saturation, and brightness; but special calibration of the wedges is necessary.

Several questions naturally arise (with regard to such an instrument) connected with the permanence of the colours of the wedges and the possibility of producing wedges identical in performance for similar instruments; for, unless various instruments will give *identical* arbitrary indications of the same colour, the special calculations necessary to interpret a measurement for any one instrument will certainly inhibit its commercial use.

Arons' Colorimeter.—Reference must be made to the colorimeter of Arons (fig. 52), in which a special device is employed

¹ *Jour. Opt. Soc. Amer.*, 1920, 420.

whereby the test colour is matched by the "polarization colours" produced by quartz plates of various thicknesses (cut perpendicular to the crystal axis) when placed between polarizing prisms. The intensity and saturation of the colour depends on the thickness of the quartz and the relative orientation of the prisms. There can be no doubt that the constancy and mutual agreement of instruments operating on such methods should satisfy the most exacting

requirements, and the arbitrary notation should be very consistent; but the interpretation of the indications in terms of hue, saturation, and brightness would need a special calibration and set of tables. There seems no reason why such tables should not be prepared once for all, and made available for future use.

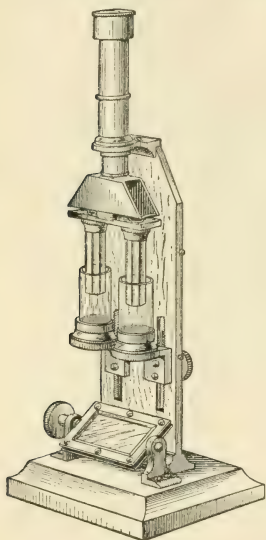


Fig. 53.—Duboscq Colorimeter

Duboscq Colorimeter.—The foregoing instruments are intended for the measurement of colour in general, but there are many purposes in commerce or industry for which it is a great convenience to be able to measure the "depth" or intensity of coloration of a substance, more especially of a given thickness of a liquid or solution. In such cases the variation of coloration takes place in a known manner, and the measurement often consists in finding the depth or thickness of a liquid necessary to produce a coloration equal to that given

by some standard, or vice versa, the effect of increasing concentration being equivalent to the effect of increasing thickness (Beer's Law; see Appendix).

The essential parts of such limited colorimeters usually consist of vertical graduated tubes with optically flat bottoms and means for varying the useful depth of liquid. Light passes from a mirror upwards through the tubes, and a suitable prism and lens arrangement is often provided in order to secure a suitably divided comparison field of view. Fig. 53 (taken from the catalogue of Messrs. Eimer & Amend, of New York, who make many types of such

colorimeters) illustrates the latest form of the Duboscq colorimeter. Thick rods of colourless glass dip into the cups containing the solutions, the light passing upwards through the solution and through the rods.

The thickness of solution used is varied by raising or lowering the cups by means of the rack-and-pinion arrangement.

The diagram (fig. 54) illustrates the type of construction of the optical parts of this and many similar instruments. Other types of colorimeter are the Campbell Hurley,¹ in which the thickness of the liquid is controlled by a side tube and plunger; the Kober (very similar to the Duboscq type); the Bock-Benedict, in which the thickness of only one member is variable; and other still more simple types.²

Nephelometer.—A method of extreme delicacy for detecting the presence of small amounts of fine precipitates in liquids is to observe the intensity of the light scattered by the particles. This light becomes measurable before the amount of the precipitate reaches a value which would be detected even by the most sensitive chemical methods.

In Kober's nephelometer the arrangement is simply that of one of the foregoing forms of limited-range colorimeter, together with a lantern and condenser apparatus, by means of which a powerful beam of light may be transmitted through the solution. In some cases (thick precipitates) it is desirable to measure the transmitted rather than the scattered light.

Accuracy of Colour Measurements.—In the chapter on

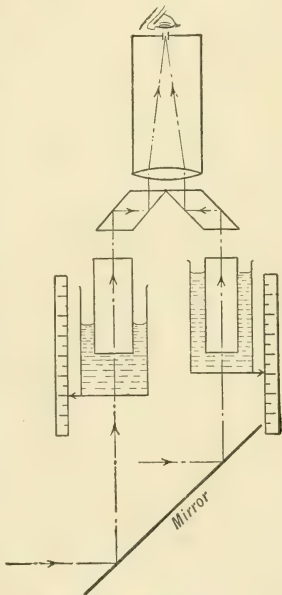


Fig. 54.—Limited Range Colorimeter (diagrammatic)

¹ See *Jour. Am. C. S.*, Vol. XXXIII, 1911, p. 113.

² For many interesting details of chemical colorimetric work using these instruments, reference may be made to *Colorimetric Analysis*, by F. D. Snell (D. V. Nostrand Co., New York).

the eye it was shown that the smallest brightness *contrast* which can be detected by the eye is about 1·6 per cent of the total brightness. The noticeable *saturation difference* is in the neighbourhood of 2 to 5 per cent. Sensitiveness to hue change is great when the hue is pure, but rapidly decreases with diminishing saturation.

Thus, generally speaking, colour measurements are very difficult, but by means of the best instruments they can be made sufficiently accurately for all commercial purposes.

CHAPTER IX

Colour Vision

It is as well to remember that the preceding study of colour has been throughout little more than a study of colour sensations, and therefore a study of colour vision. "Colour" has no existence in the outside physical world. There are certain wave-motions, it is true, but colour is a *mental* phenomenon.

In the instinctive search after truth, mankind from the earliest times has sought to co-ordinate phenomena, to recognize underlying principles, and further to state these principles as generalizations. The main use of such generalizations is to attempt to pass from observed phenomena to the prediction of the phenomena which have *not* been previously noticed. It is certainly true that the recognition of these underlying harmonies of nature is one of the chief mental pleasures we can ever experience.

Westaway says, in his *Scientific Method*: "In the earlier stages of scientific inquiry, generalizations are more or less empirical. We have first to be satisfied with 'facts' which we check and correct, label and classify, and thus do our best to ensure accuracy and orderliness. That which has to be 'explained' must be clearly and distinctly set out before we can attempt to explain it. In other words empirical generalizations must precede generalizations of 'strict' determination. We must first ascertain the laws of phenomena; the consideration of causes must come later. Obviously then our generalizations vary greatly in finality; but as our knowledge grows so they increase in comprehensiveness and certainty."

Frank Allen¹ gives a striking picture of the heterogeneous mass of speculations and theories which have grown out of the discussion of colour vision. Physicists, physiologists, and psychologists alike have seen the problem from their individual view-points, and have evolved so-called "theories" of colour vision, of which the early

¹ *Amer. Jour. Physiol. Opt.*, April, 1920.

ones have only too often suffered from the narrowness of outlook consequent on the one-sided education of their authors.

In fact the ideas of most of us suffer from the same cause, but we must at all events make an honest attempt to review the more useful theories, and set them in their proper position with respect to their pretensions and performances.

We are to start with a collection of facts. So far in the present book we have set forth many of the main basic facts, and in this and the next chapter we shall review many more. Let us recall some of them.

1. The existence of red, yellow, green, and blue as characteristic and apparently unconnected sensations, not forgetting "white".

2. The existence of 148 distinguishable hues and the peculiar nature of the curve connecting distinguishable hue change with wave-length.

3. The peculiar nature of the curve connecting visibility of radiation with wave-length; the Purkinje effect.

4. The possibility of reproducing all possible hues from monochromatic spectral red, green, and blue or violet in suitable proportions, which can be exactly measured for primaries of definite wave-length and which are uniform for the majority of human beings.

5. Our definite knowledge regarding the construction of the retina and its reactions to light. Modern knowledge of the characteristics of the propagation of impulses in the nervous system.

Some topics which we have not yet fully discussed include:

6. After-images and the results of experimental work on colour fatigue.

7. Changes of hue on adding white to some "pure hues".

These last two must also be brought into line with any theory which may be propounded.

It cannot be too strongly insisted in this connection that the most important desideratum at the present stage of the inquiry is to ascertain the facts, as many of the arguments at present being employed between the rival schools are based on unsound experimental work. It is not until the *untruths* have been exposed that the theories can be viewed in the true light. The situation is rapidly changing, however, and modern work is doing much to clear the air.

Now it has been very truly said that we only begin to *know* facts regarding a physical entity or phenomenon when we can make measurements regarding it or its parts. Referring to our table of facts, No. 1 (the apparent independence of certain hue sensations) appears more remarkable to some persons than to others. The complete independence of yellow as a sensation is largely a matter of opinion—some persons at least call it “reddish-green”.

In Nos. 2 and 3 we are on the more definite ground of measured quantities, and there can be no dispute as to the establishment of the main facts.

In No. 4 it should be insisted that the groundwork of experimental fact is just as well established. It was, of course, the *extraordinary* fact that all hue sensations and white could be built up of three primaries that early attracted the attention of the scientifically minded of bygone days. Their confident suggestion that such experimental facts must be caused by some fundamental three-unit construction of the retino-cerebral receiving apparatus was an entirely sound step. Difficulties arose, however, in the minds of physiologists and psychologists who failed to find in the suggestion sufficient food for their own particular thought.

The prejudice against the three-colour or “trichromatic” theory is presumably the factor which has kept many non-physicists from the study of the numerical facts, and this is a misfortune, because, while it cannot be maintained that the trichromatic theory is in any way perfect, yet the main array of measurements clings closely around its structure, so closely in fact that some maintain that the theory is little more than the ordered facts it purports to explain. This is flattering the trichromatic theory; the connection between theory and practice is by no means quite so well established, but if it be true that the vast array of colour-mixing phenomena are all reducible, with a few exceptions, to the terms of a simple theory of the various stimulations of three fundamental sensations, if it be true again that the theory can explain to some extent the phenomena of our headings Nos. 2, 6, and 7, then the conclusion is irresistible that these fundamental sensations ought to be the starting-point for a strong theory seeking to explain the mechanism by which the effects of light are transferred from the eye to the nervous system and the brain.

Statement of the Theories.—We shall now give a general statement of the purport of the trichromatic theory and then proceed to a description of two psychological theories and one physio-

logical theory, those of Hering, of Mrs. Ladd Franklin, and of Dr. Edridge-Green respectively.

Trichromatic Theory. — The original three-colour or trichromatic theory of colour vision first proposed by Young, and afterwards elaborated by Helmholtz, supposed that there are three types of colour-receiving apparatus in the eye. Light of any spectral wave-length may stimulate all of these, but to unequal extents. The stimulation of one of the three gives rise to a "pure" sensation of red, green, or violet; any one wave-length of light may not produce a psychologically pure hue sensation, but the stimulation of the violet and green sensations by the red wave-lengths is supposed to be relatively small, and so on. The theory has been modified considerably in late years, notably by recognizing that certain ranges of wave-length may *not* affect all three sensations.

Hering's Theory. — The main aspect of colour vision to Hering seems to have been our point 1, namely, the marked differences between red, yellow, blue, and green, and between white and black. It is naturally more easy for a psychologist to conceive of black as an active sensation than for a physicist.

Hering also realized the apparent destruction of "intense" hue when certain of the primaries combine, as when yellow and blue lights mix to form white. Hence he assumes the presence in the retino-cerebral apparatus of three substances. The first he supposes to be decomposed by light of all wave-lengths in amounts corresponding approximately to the visibility of radiation; while in darkness, or the absence of light from the retina, it is built up or reconstituted. These "chemical" changes are in some manner "sensed" as light and darkness.

The second substance is decomposed at a maximum rate by red light, and reconstituted at a maximum rate by green.

The third is decomposed at a maximum rate by yellow, and reconstituted at a maximum rate by blue.

The yellow is thus elevated to the dignity of a primary sensation, and on this theory it will be seen, for example, that red and yellow, green and blue acting together in certain proportions give only a white or grey sensation (see Titchener's colour pyramid, fig. 15).

Troland cites certain objections to, and deficiencies in, the theory in this, the original form. What would happen, for example, if light or darkness were continued indefinitely?

In the indefinite continuation of fairly bright red light on the

retina, the second substance should be continuously decomposed until it is all consumed, and if any more could be made it would as quickly vanish. This point of stability should correspond to a grey; but it is our experience that the red sensation never totally disappears though colour fatigue *is* present.

Again, we must reach a point of stability in complete darkness, but when the first substance is entirely reconstituted the sensation of "blackness" should vanish. What is left? We should again expect a grey, but this is hardly borne out by experience.

The effect of red and green acting together is said to destroy any sensation due to the second substance and leave a grey. We shall naturally inquire: "What red, and what green?" The spectral complementary hue to the hue of the extreme red is located at 49μ . This point, however, is said not to be a psychological primary; in fact a true psychological primary green mixed with red is declared by Mrs. Ladd Franklin always to produce the sensation of an unsaturated yellow. It looks as if Hering would have done better to have chosen red, yellow-green, blue-green, and violet for his primaries. Helmholtz suggested the replacement of red by red-purple.

It is, of course, true that the theory might be adapted to express the numerical facts of colour mixture on a "four-colour" instead of a "three-colour" basis, but this seems somewhat artificial and redundant.

The apparent antagonism of red and green, resulting more especially from sector disc experiments, is, from another point of view, merely the inevitable result of the union of very unsaturated or impure colour sensations. There can be no controversy as to the production of a yellow-hued component in the mixed sensation.

Why is it then that psychologists maintain the independence of the yellow sensations? Is it not the fact that human thought on any particular fact or sensation is profoundly modified by associated ideas, and that the main ideas associated with the sensations of red, yellow, and green are strikingly different? Fire and blood, the "fierce" elements in life; flowers, autumn and harvest hues, decay and stillness; the quiet yet powerful hue of forests and fields, the promise of spring in growing crops—all these things have profoundly influenced us, and our thought of colour is inevitably associated with and influenced by them.

It may be then, that, while the psychologist is correct in maintaining the individuality of yellow as an "idea", it is not necessary

to conclude that the individuality is caused by any physiological peculiarity of the retino-cerebral *receiving* apparatus. Such distinction may well have its origin at a comparatively late stage in the production of the sensation which is finally presented to consciousness, and may take place only in the higher, mysterious regions of the brain. The trichromatic theory may serve us well enough as an explanation of the "telephone-like" system of which we conceive as connecting the retina and the brain.

With this line of thought the merit of the psychological theories can more truly be discussed, and it will thus be realized that they are not necessarily antagonistic to the trichromatic theory.

Ladd Franklin Theory.—The original statement of the Ladd Franklin theory was also in more or less chemical terms, and referred to a substance supposed to exist in the retina. This (according to the theory) is broken down by white light, or light of any wave-length, in varying degrees, and the products of decomposition react on the nerves to produce the white light sensation. Absence of excitation corresponds to "black" or darkness, and in this condition the substance may be reconstituted by natural means.

The substance exists again in a second stage of differentiation, and then presents two parts to the action of the light stimulus. One part is decomposed at a maximum rate by blue light and the other by yellow light, but the *simultaneous* decomposition of the two parts produces a grey equivalent to the result of the decomposition of the primitive form.

In the third stage the component sensitive to yellow is separated into red-sensitive and green-sensitive portions. As before, stimulation of one component and the breaking down of the corresponding substance produces the characteristic hue sensation, but the stimulation of both produces not grey, but the original derivative—yellow.

In this theory the main visual facts of colour sensations are fairly well explained; many of the objections to the older Hering theory are avoided, and, just as before, the numerical features of colour mixing could be accurately explained. Troland¹ points out, however, that the theory as it stands would require five different types of nerve-impulse or five differentiated nerves to convey a single definite colour sensation to the brain. Further, the possibility of the existence of such a chemical substance is apparently somewhat problematical. He is led to the conclusion that while a mechanism similar to that outlined in the theory would

¹ *Amer. Jour. Physiol. Optics*, Oct., 1920.

explain a great many of the psychological facts of colour vision, there is no justification for the assumption that the mechanism must be one of a chemical nature or that it should take place in the retina. He prefers to locate the process in the higher centres of the cerebral cortex.

It will be noted that the theory sets out very suggestively the lines of a possible evolutionary progress in the development of colour sense. The achromatic "rod vision" first of all appears. This is followed by a yellow-blue differentiation, and lastly by a differentiation of the yellow into red and green. The greater persistency of the "older" type of sensation would throw light on the origin of the Purkinje effect.

Edridge-Green Theory.—The theory of Dr. Edridge-Green has attracted an increasing amount of attention in late years, and is of interest because it expresses very well the point of view of physiology. Its main features may be summarized as follows:

The visual purple is secreted by the "rods" of the retina and liberated by them under the *stimulation* of light. The rods do not otherwise participate in the origin of the nervous impulses due to light.

The visual purple surrounding the ends of the cones absorbs light, and chemical changes are produced which in some manner stimulate the nerve endings, thus producing an impulse which is conveyed to the brain. The intensity of the sensation at the ends of the spectrum may be lowered in some cases, owing to variations in the constitution and sensitiveness of the visual purple.

To quote a summary for further points:

"The character of the impulse set up differs according to the wave-length of the light causing it. Therefore in the impulse itself we have the physiological basis of the sensation of light, and in the quality of the impulse the physiological basis of the sensation of colour. The impulse, being conveyed along the optic nerve to the brain, stimulates the visual centre, causing a sensation of light, and then, passing on to the colour-perceiving centre, causes a sensation of colour. But though the impulses vary in character according to the wave-length of light causing them, the colour-perceiving centre is not able to discriminate between the character of adjacent impulses, the nerve cells not being sufficiently developed for the purpose. At most, seven distinct colours are seen, whilst others see in proportion to the development of their colour-perceiving centres."

The apparent trichromatism of our vision is thus explained on

the basis of an imperfect development of the colour-perceiving centres. In the evolutionary development of the colour-sense the radiations most differentiated physically are supposed to have been first to be distinguished, and the ends of the visible spectrum first showed differences of hue. Yellow was differentiated *after* red and green, so that when red and green act together it is said to be "obvious" that the yellow sensation replaces the more primitive one of "red-green". If red, green, and violet (or any three sensations thus distributed fairly widely over the spectrum) are present together, the energy curve will be determined sufficiently nearly by the three points, and the impression of the visual colour-receiving centre will be identical (owing to this imperfect discrimination) with the result of a radiation containing *all* the components suggested by the energy curve. These are a few points only in the general theory. Houston¹ has shown at greater length how the facts of colour-mixing can be accounted for on this theory.

In formulating this theory and defending it, more especially in regard to the portion which connects the colour sensation with the quality of the visual nerve impulse, considerable emphasis was given to the apparently limited number of distinguishable hues in the spectrum, as measured by a special apparatus used by Dr. Edridge-Green. In this matter he is in direct conflict with the results of Steindler, who finds about 120 steps of hue against 29 found by Edridge-Green. Steindler's figures are confirmed by recent results obtained at the Kodak laboratory (America) by Reeves and others, and it appears that the discrepancy is due to the imperfect suitability of Edridge-Green's apparatus,² in the construction of which the condition of producing a sharp boundary between two *uniform* patches, whose hue is to be contrasted, had not been realized. Gradual changes of hue in a single patch are most difficult to detect. There must be then at least 120 different "qualities" of visual nerve impulse to explain "hue" before variations of intensity and "accompanying white" are considered.

Another experiment which is considered decisively to disprove the trichromatic theory is described.³ It is said that if an eye fatigued with sodium light views a spectrum, the yellow is diminished

¹ *Phil. Mag.*, 38, p. 402, 1919.

² *Hunterian Lectures in Colour Vision* (Kegan Paul, Trench, Trubner, & Co., London), p. 72.

³ *Hunterian Lectures in Colour Vision* (Kegan Paul, Trench, Trubner, & Co., London), p. 22.

in intensity, but the red and green "show not the slightest diminution". If this were true it would go far to cast doubt on the claims of the trichromatic theory. However, the experiments of Allen,¹ who investigated such fatigue effects numerically, directly contradict the statement and indicate that the *maximum* fatigue is in the green and red. The general results of Allen's work will be described later. They support the trichromatic theory.

Burch² also describes experiments leading to the same conclusions.

Another factor, for which future theories of colour vision may have to allow, is the principle established by Adrian and Lucas, known as the "all or none" action in nervous response, from which it would appear that the impulse which passes along a nerve fibre is incapable of quantitative variation. The work of Troland is said to indicate that the principle applies to optic nerve fibres. Hence the variation of frequency of stimulation of a single nerve fibre is the only means of differentiation of transmitted sensations. It seems impossible that the frequency should be related to that of the stimulating light, so that if an individual nerve corresponds to a definite location on the retina, and frequency of nerve impulse corresponds to *intensity* of light, how are we to explain hue sensations?

We are left a loophole in the apparent fibrous character of insulated nerves.³ Already it seems necessary to allocate one nerve to three "cones" and perhaps more "rods" in the major portion of the retina, but if it is possible to conceive that the separate fibres of a nerve are capable of transmitting separate impulses, the assignment of three nerve fibres to each cone for a trichromatic transmission of hue sensation to the brain makes no illegitimate demand on our reason. It seems that the "all or none" principle would be extremely hard to reconcile with the Edridge-Green theory of the nature of hue sensation.

In spite of the difficulty connected with the acceptance of the second part of the theory, the suggestion as to the function of the visual purple is especially suggestive and valuable. The characteristic absorption-curve of the visual "purple", which has its greatest absorption in the yellow, would go far towards explaining the spectral "visibility" curve. The analogy of the sensitization of photographic plates is helpful in considering the matter.

¹ *Amer. Jour. Physiol. Optics*, April, 1920.

² Burch, *Phil. Trans. Roy. Soc.*, B. 1899.

³ J. W. French, "The Unaided Eye", *Trans. Opt. Soc.*, XXI, No. 4.

As a last item it may be mentioned that Dr. J. W. French¹ finds considerable evidence that three parts of the retinal "cones" may be the colour-receiving centres, the blue, green, and red receptors being placed in this order towards the entering light. This suggestion would tend towards an explanation of the threshold colour phenomena and is otherwise of considerable interest.

This review must complete the sketch of the main theories of colour vision at present extant.

It is a long chain of causal events which ends in the production of a colour sensation, and the greatest difficulty which has beset colour theorists is that of assigning the stage of origin of its various characteristics. Physicists, psychologists, and physiologists alike have invaded each other's domains. Is it too much to hope that some form is emerging from the prevailing welter of confusion?

Measurement

of the Hue Sensations in the Spectrum.—The growing consensus of opinion as to the fundamental nature of the trichromatic transmission of colour sensations makes the numerical measurement of the component sensations for different wave-lengths in the spectrum a matter of great importance.

It will be well to study for a beginning the simple method employed by Clerk Maxwell, whose apparatus is illustrated in fig. 55.

On placing a narrow slit in the plane of the spectrum formed by an ordinary spectroscope and looking through it, the prism face appears to be uniformly and brightly lit up by the spectral colour corresponding to the location of the viewing slit. If the collimator slit is moved the whole spectrum shifts, and the colour in the prism face is modified accordingly. By using two or more collimator slits the retina may thus be made to receive the united radiations, focused in the image of the prism face, from two or more narrow parts of the spectrum.

Maxwell placed the three collimator slits so that a "good" red, green, and blue were united; corresponding wave-lengths were indicated by a scale, and relative brightness was controlled

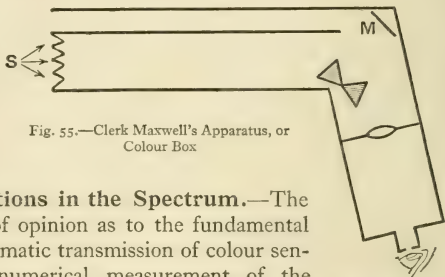


Fig. 55.—Clerk Maxwell's Apparatus, or Colour Box

¹ *Trans. Opt. Soc.*, XXI, No. 4.

by a measured variation of slit width. The apertures were illuminated by light reflected from a white sunlit card, and the mirror M was adjusted so that a patch of the original white appeared immediately against the prism.

With the slits in the standard position a , b , and c they can be varied in width till the prism appears white. In the following equations an expression like "10*b*" means a slit width of 10 at standard position b .

An equation may thus be formed immediately from experiment; suppose

$$18.6a + 31.4b + 30.5c = \text{white} \dots \dots \dots (1)$$

One of the slits can now be slightly moved in the spectrum and a fresh match made, producing the equation:

$$17.5a + 30.7b + 44.0c' = \text{white, same intensity as in (1)}.$$

Subtracting we find

$$1.1a + 0.7b + 30.5c = 44.0c'.$$

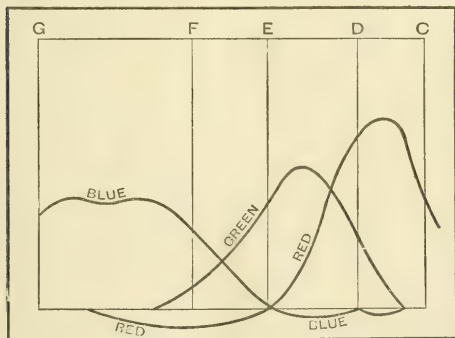


Fig. 56.—Clerk Maxwell's Curves

We have expressed the composition of the unknown c' in terms of the necessary slit-widths of the standards for its formation.

The colours selected by Maxwell for the standards corresponded to wave-lengths $.63 \mu$ (red), $.528 \mu$ (green), and $.457 \mu$ (blue). His curves are given in the diagram¹ (fig. 56). They represent the

¹The wave-lengths of the Fraunhofer lines in the spectrum are: C = $.656 \mu$, D = $.589 \mu$, E = $.527 \mu$, F = $.486 \mu$, G = $.430 \mu$.

composition of the sensations, and would have been modified had he selected other slightly different primaries.

It will be noticed that the curves actually go "below" the base line. Maxwell finds that some of the spectrum colours contain a certain amount of white sensation and by no means give "pure" hue sensations. For example, it was found impossible to reproduce the spectral yellow (in its ordinarily saturated form) by combining spectral red and green. Thus in fig. 56 it is seen that in the yellow of the spectrum the ordinate of the blue sensation curve is negative. This indicates that blue must be added to the spectral yellow (thereby diminishing its saturation) before it can be matched by a mixture of the red and green primaries.

Primary Hue Sensations.—"Slit width" being at best an unsatisfactory means of measuring the proportionate stimulation of a sensation, workers have been led to the postulate that equal amounts of *stimulation* of three fundamental hue sensations produce white.

There are small regions at each end of the spectrum which appear to be quite uniform in hue. A natural first supposition will be to suppose that these regions cause fundamental hue sensations. On this supposition the complementaries of these extreme red and violet hues will be at the places in the spectrum where green sensation and violet sensation stimulations are equal, and where green sensation and red sensation stimulations are equal, respectively.

Adding the complementaries to the red and violet in the proper proportions, two whites are produced which may be equalized in intensity. The following equation results: (red stimulation) + (complementary green and violet stimulation) + (unknown white stimulation) = (violet stimulation) + (complementary red-and-green stimulation) + (unknown white).

The unknown white stimulation is not large. We will suppose it is negligible in each case for the present purpose

Adding the two *complementaries* only (green + violet, and red + green) in the quantities used in the above equations, we evidently produce a combined sensation, in which the red stimulation is equal to the violet sensation, and an excess of green is left, which corresponds in *hue* to pure green sensation; this hue can thus be found in the spectrum *on the above assumptions*. Abney finds the point to be $\cdot 515 \mu$. Allen describes other means of locating the pure sensation hues. See a later paragraph.

It is supposed, however, that the green sensation excited by the spectral green is an unsaturated sensation. It is evident that steps to ascertain the relative amounts of the hue sensations in this and other spectral regions will depend on *luminosity* measurements.

The relative luminosity of the various spectral regions for constant slit-width and a known type of dispersion has already been discussed, and results are therefore available which give the luminosity of a spectral colour as compared with a standard white in terms of slit-width.

In order to obtain the luminosity of the white in the standard green, it is mixed with red to match a spectral orange-yellow diluted with white. A luminosity equation results:

$$a \text{ (orange yellow)} + b \text{ (white)} = c \text{ (red)} + d \text{ (green)}.^1$$

Assuming that neither the red nor the orange contain white, the equation is transformed to

$$a \text{ (orange yellow)} = c \text{ (red)} + d \text{ (green)} - b \text{ (white)}.$$

∴ Percentage of luminosity due to the pure green sensation in this green spectral light = $\frac{d-b}{d} 100 = 69$ per cent as measured by Abney.

The procedure is now on the lines of Maxwell's method. Equations of the type:

$$\begin{aligned} L_1 \text{ (pure red)} + L_2 \text{ (pure green + compound white)} \\ + L_3 \text{ (pure violet)} = \text{white,} \end{aligned}$$

in which the terms represent luminosities (apparent brightness as compared with standard white), can be varied in the same manner by an alteration of one term in the equation, and thus the "luminosity of sensation" curves are completely derived. As the white sensation in the spectral green primary has been allowed for, negative values of the ordinates are avoided.

Fig. 57 shows the "sensation luminosity" diagram from which the percentage composition of the luminosity of any spectral colour in terms of pure red, green, and "blue" luminosities may immediately be found. See Appendix, Table 7.

¹ There has been of late some tendency to question the assumption that the *luminosities* of different hues always add in the above simple manner. Experimental work on this point is still in progress, but it is hardly likely that the voluminous work of Abney and Ives confirming its correctness will be discredited.

The above is a sketch of the methods described by Abney,¹ who considered that "blue" was a primary sensation, as violet could be formed of blue and red. He therefore split his violet luminosities into 72 per cent red and 28 per cent blue luminosities.

It is just as true, however, to say that blue may be formed of violet and green.

If violet is considered a primary, we are saved the necessity of supposing an increasing red sensation stimulation in the shorter wave-lengths, which appears undesirable from a physical point of view.

Another method of presenting these results is to bring them into

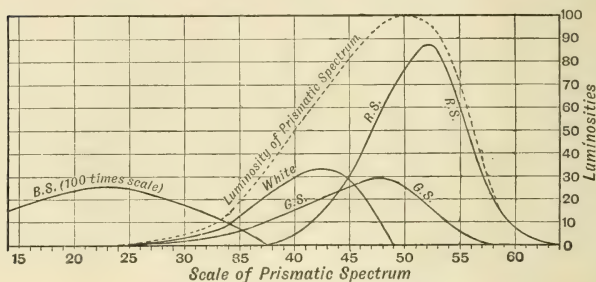


Fig. 57.—Sensation Luminosity Curves (Abney)

accord with the proposition that equal stimulation of all three sensations shall produce white. The area under each luminosity curve is a kind of integrated stimulation taken over the whole spectrum; by making the areas under the three curves equal by altering the ordinates in the required ratios, we obtained psychological stimulation or "sensation" curves.

Abney's sensation curves for a normal spectrum in terms of red, green, and blue primaries are shown in fig. 58. The corresponding curves of König and Dieterici with red, green, and violet primaries are shown in fig. 59. Note that the wave-lengths are plotted in the reverse order. *These results are of the greatest importance in colour measurement, no matter what the final truth of any theory may be.*

The curves for the composition of spectral sensations should be carefully studied, in order to judge how the intermediate hues

¹ *Researches in Colour Vision.*

of the spectrum arise. It is also extremely interesting to compare the colour-sensation curves with those showing the variation of the hue difference limen with the wave-length. Referring to König's results (fig. 59), it will be seen that at about $\cdot 49 \mu$ a small change

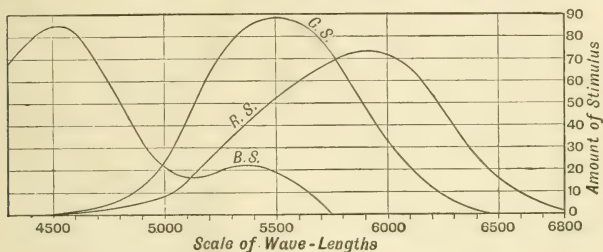


Fig. 58.—Sensation Stimulation Curves (Abney). (See table, p. 181.)

of wave-length involves rapid changes in the proportionate stimulation of the various sensations, and this is the region at which the perceptible change in hue with wave-length is most marked (see fig. 58). There is another maximum in the hue change at $\cdot 57 \mu$,

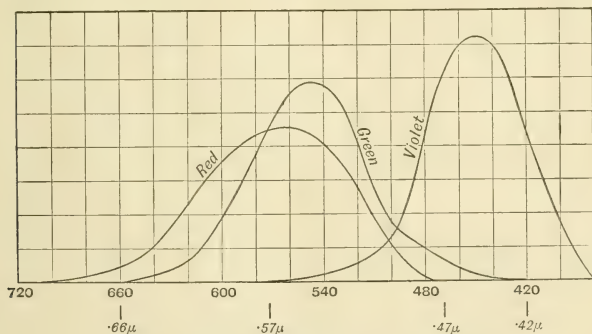


Fig. 59.—Sensation Stimulation Curves (König and Dieterici)

where the red and green sensation curves cross each other, and the blue sensation disappears. The secondary maximum at $\cdot 44 \mu$ is located near the peak of the violet sensation curve and where the green sensation vanishes. There is also another secondary maximum at the "long wave-length" end of the green sensation.

Such results must not be taken as proving the truth of the trichromatic theory, but they are an excellent example of the manner in which a working theory will forecast useful results. Regarded from one point of view the hue limen curve and the set of sensation curves may be regarded simply as differing empirical expressions of the same underlying facts.

Determination of Hue, Saturation, and Brilliance of a Surface from Spectrophotometer Readings.—A spectrophotometer can be employed to find the characteristic percentage reflection or transmission coefficients (as compared with white in the case of reflection) throughout the spectrum. Assuming that we now desire to find the characteristic hue, saturation, and brilliance corresponding to the substance when illuminated by a definite type of light, we obtain a table of spectral luminosity values corresponding to this light, and thus calculate the luminosity values in the *reflected* light. By means of a table (Appendix, Table 7) showing the percentage composition of spectral luminosities in terms of red, green, and blue sensations, the sensation luminosities in the reflected light can then be obtained and plotted against a scale of wavelength. The areas under the three curves now represent the total luminosities of the red, green, and blue sensations, and these areas can be found graphically.

We have now to find the proportion of white luminosity and the resultant hue. To do this we must calculate the relative stimulations of the primary sensations by the reflected light, and this is done by multiplying the total luminosity values by the same factors as were necessary (see above) to make the areas equal under the red, green, and blue curves for the ordinary spectrum. For the arc light and the particular dispersion used by Abney the factors were 2.3 and 1.78 for green and blue respectively, but these would differ for other illuminants and dispersions, and would have to be found separately for special cases.

To take a concrete example, a sample of an emerald-green pigment was submitted to spectrophotometric examination against a sample of white, and the resultant luminosities in the sensation given by the reflected light were calculated as:

Red sensation	=	202
Green „	=	133
Blue „	=	1.418

Total area under luminosity curves for white	=	830
„ „ „ green pigment	=	336

The stimulations are: red = 202, green = $133 \times 2.3 = 306$, blue = $1.418 \times 178 = 252$. Amounts equal to 202 in each of these stimulations group to form white, leaving a residual of red = 0, green = 104, blue = 50, whence the luminosities of the green and blue are $\frac{104}{2.3} = 45.2$, and $\frac{50}{1.78} = 28$, respectively. The tables now have to be consulted till a place is found where, after deducting white, the ratio of the green to blue sensation is 45.2 to 28. This is found at $\lambda = .507 \mu$. The saturation fraction is given by $\frac{45.2 + 28}{336} = 0.135$ or 13.5 per cent. It could otherwise be found directly if desired.

The "brilliance" of the pigment is given by $\frac{336}{830}$ or 40.5 per cent.

A table of typical results is given in the Appendix, Section 5.

Change in Hue of Spectrum Colours.—Abney¹ finds that the addition of white² to certain spectrum colours causes apparent changes of hue. He describes the effect of the addition of white light as follows: "In the red the colour becomes pinker as more of the white light is added, the scarlet becomes orange, the orange yellow, and the yellow green. The yellow-green does not suffer a change, but as the green is approached it becomes yellower in hue, and as the white light passes over the green this same tendency to yellowness appears. In the blue there is not much alteration, but as the violet is approached a very small quantity of white will make it appear salmon coloured."

On investigation he finds that, for example, a certain colour ($\lambda = .5611 \mu$, of luminosity 100) may have the composition in luminosities:

	R.S.	G.S.	B.S.
Adding white (luminosity 60)	55.45	32.6	0
	41.4	18.6	0.24
We have thus the composition of the mixed light	96.85	51.2	0.24

It would appear from Abney's results that the eye judges the final hue irrespective of the 0.24 blue, and selects the hue in the spectrum where the red sensation and green sensation have the proportions shown in the table.

The hue which matched the mixture is found at $\lambda = .5677 \mu$ approximately.

¹ *Proc. Roy. Soc., A.* Vol. LXXXIII, 1909.

² The white of the arc light.

It will be realized that these phenomena are of considerable importance in colorimetry, especially in the instruments where white is mixed with spectral colours. Taking for example an extreme case, it appears that in order to match a very unsaturated green we might have to begin with a hue which, before dilution, appears more nearly a blue. From the foregoing words of Abney queer effects might be expected when oranges and violets of low saturation have to be measured. Effects of this kind would tend

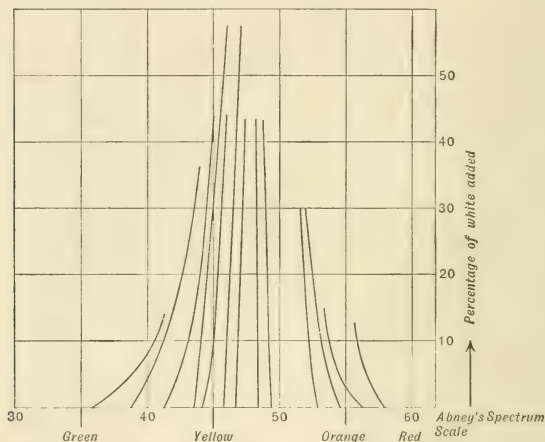


Fig. 60.—Abney's Diagram of Results

to make the indications of such colorimeters as those of the Nutting type somewhat more empirical than would otherwise be expected, and would also complicate greatly the simplicity of the three-dimensional colour systems which have been described in the foregoing pages. Fig. 60 shows Abney's results for the changes of hue consequent on the mixture of white light with spectral colours. From the point of view of modern colorimetric requirements the work needs considerable extension.

Visual Fatigue.—Dr. Frank Allen¹ uses the critical "flicker" speed as a method of investigating fatigue. If a small patch of light seen in a dark field of view be lit and darkened for equal

¹ *Amer. Jour. Physiol. Optics*, April, 1920.

intervals, the alternation cannot be perceived if it takes place sufficiently rapidly, as everybody who has seen a kinema entertainment knows. As the frequency of alternation diminishes, however, there will be a speed at which the flicker becomes visible to the eye. Porter's work¹ on the persistence of vision gave the following relations connecting N , the critical frequency, with field brightness I .

$$N = 12.4 \log I + 24.9 \text{ (relation for higher intensities),}$$

$$N_2 = 1.56 \log I + 19.6 \text{ (relation for lower intensities down to the threshold.)}$$

Fig. 61 shows some relative results.

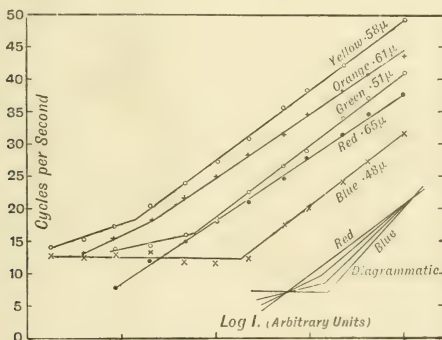


Fig. 61.—Critical Frequencies

It was at one time believed that this method would be satisfactory for *photometric* purposes, but, of course, the critical frequency depends entirely on the condition of the eye. The luminosity curve of the spectrum has been determined in this way by Nutting, Ives, and Allen.

The method works equally consistently for luminosity measurements with coloured light as with monochromatic, and we shall refer to it again below.

Colour Fatigue.—If the eye gazes at a bright patch of pure colour surrounded by darkness for, say, 30 sec., and then immediately at a white surface, a patch of similar shape but of approximately complementary colour will appear in the field of

¹ Porter, *Proc. Roy. Soc.*, 70, 313, 1902.

view (the negative after image). Colour sensations, then, may be fatigued independently. This subject is, of course, at once open to accurate experimental investigation, and Abney describes certain very interesting experiments performed with the colour-patch apparatus.¹

In one of the experiments *one* eye is fatigued with yellow light by looking through a slit placed in the yellow of the spectrum at the point where the "equal area" sensation curves for red and green cut—or where the stimulation of the red sensation is equal to that of the green. In order to have a measure of the luminosity of objects as seen by the fatigued eye, an arrangement is made by which a patch seen by this eye only is contrasted with another white patch seen by the unfatigued eye only. This is quite easy to do with a thin black screen the plane of which passes between the two eyes. In this way the luminosity of pure red and pure green patches seen by the yellow-fatigued eye have been measured, and both are found to be diminished, thus proving that part at least of the yellow sensation is connected with both red and green.

Another experiment described by Abney is the fatiguing of one eye by a pure red. This eye then views a patch illuminated by light of $\lambda = .576 \mu$ (where Abney's equal-area sensation curves intersect). The unfatigued eye now makes a match of *hue* with the screen arrangement, and the match is found to be approximately $\lambda = .501 \mu$, a blue-green which, according to the sensation curves, contains a good bit of white. Under these conditions, however, the blue-green spectrum colour seen by the unfatigued eye looks very pale in comparison, and Abney concludes that the green sensation experienced by the fatigued eye is very much purer than can ever be felt normally, except by a partly red-blind person. In the experiment described, the brightness of the pure red sensation is reduced to about one-third by fatigue.

Allen's Investigations.—The method employed by Allen (described above) is very fruitful in this connection. He finds a critical frequency curve for an eye both when unfatigued and when fatigued by definite exposures to radiations of varying wave-length.

The results afford an interesting commentary on the sensation curves derived from independent measurements. As might be expected when the eye is fatigued by light of wave-length near $\lambda = .57 \mu$, where the red and green stimulations are equal, the visual

¹ *Researches in Colour Vision.*

luminosity of the whole spectrum is affected evenly, as, of course, the *luminosity* is made up almost entirely of red and green sensations. Where the sensations are unequal in the fatiguing light, however, the curves are no longer parallel. (See figs. 62 and 63, which show critical flicker *periods* under fatigue conditions as compared with the normal.) Allen thus finds several transition points at places where sensations should equalize or vanish, and concludes that primary physical sensations (red, green, and violet) actually exist. He criticizes and com-

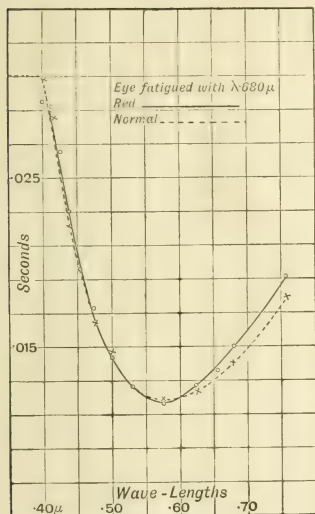


Fig. 62.—Allen's Fatigue Curves

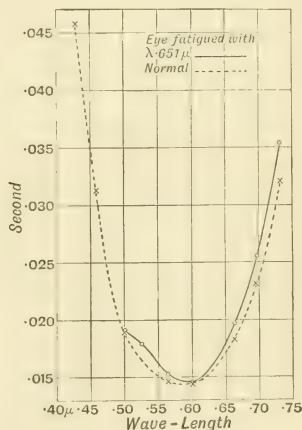


Fig. 63.—Fatigue with Orange Light

pares, with the results of his own work, the positions of the transition points and regions of pure colour sensation as given by other experiments. Allen's suggested primaries are red, green, and violet. The red sensation is pure between the red end of the spectrum and $\cdot 66 \mu$, the green is excited by some wave-length between $\cdot 57 \mu$ and $\cdot 47 \mu$, and the violet is pure between the wave-length $\cdot 42 \mu$ and the violet end of the spectrum.

Perhaps the most interesting and suggestive part of the paper, however, is that which describes the effect of colour fatigue induced by composite whites made up of three colours. Such fatigue apparently differs very greatly from that induced by the original white

light. These results expose a definite inadequacy in the trichromatic theory as originally stated, but no final judgment can yet be passed on this matter. Some later work of Dr. Edridge-Green (*Nature*, 25th Aug., 1921, p. 826) will be of interest in this connection. In colour vision we are concerned with the retina, nerves, and brain. All three are concerned in the production of a sensation, so that the trichromatic action may still be legitimately attributed to the transmission portion (or other part) of this very complicated apparatus without expecting to find therein the whole explanation of every experimental fact.

CHAPTER X

Colour Blindness

Deficiencies in colour vision may be congenital or may arise through ill health or disease. In cases of acquired colour deficiency the defect often commences at the fovea. As has already been hinted, the main phenomena are in accord with the supposition that one or more of the trinity of chromatic sensations is lacking or deficient. From another standpoint colour or hue blindness may be regarded simply as a type of undeveloped mental colour-detecting capacity.

Total "colour blindness" involves an inability to perceive any variation of *hue* in the spectrum. Light and shade can still be distinguished. Such cases are comparatively rare.

In types of partial colour blindness it is found that in many cases hue sensations are still excited by the shorter wave-lengths which differ markedly from others excited by the longer wave-lengths. These "hues" may be separated by a hueless grey interval if the hue blindness is considerable. To some persons, however, the longer red wave-lengths are totally invisible; their hue sensation starts at shorter wave-lengths. To others the extreme red is quite easily seen, and the patch of grey in the spectrum may be broader. These latter two cases refer to serious hue blindness, but there are many persons who, with or without the characteristic shortening of the red, fail to *name* yellow as a characteristic hue differing from the colour sensations which ought to be experienced at $\cdot 50 \mu$ or $\cdot 65 \mu$ (the normal's green and red).

Others again will name red, yellow, green, and violet as characteristically differing hues, but will fail to detect the more subtle differences of the blues.

Note that we have so far refrained from speculation as to the nature of the hue sensations which the hue-blind subjects may experience.

Types of Colour Blindness.—The discovery by Young in

1807 of the colour blindness of Dalton led to an immense amount of experimental work on the phenomena of colour blindness. Amongst the methods employed, those of colour mixture naturally took an important place. It was discovered that, whereas the normal sighted require three primary hues to match the full range of visual hues, two primaries suffice for a large range of colour-blind subjects to produce the full range of hue sensations possible to their vision. Hence the terms *trichromat* and *dichromat*. The intermediate class, which makes colour matches differing to some extent from the normal, are classed as *anomalous trichromats*.

There is apparently a considerable body of evidence to indicate that there are two well-marked classes of dichromats. Their characteristics may be described by reference to the experiment by which monochromatic yellow is matched by a mixture of a spectral red and spectral yellow green. By altering the ratio of red to green a mixture of varying luminosity is obtained, which can be matched in *brightness* by altering the intensity of the yellow. For the first class of colour blindness a very red mixture will match with a dark yellow, and a very green mixture with a light yellow. For the second class the red mixture above appears much too bright, while the green mixture is too dark. V. Kries calls these first and second classes *protanopes* and *deutanopes* respectively. It is remarkable in the above case that by trial certain luminosity matches may be found which will satisfy both protanopes and deutanopes. When this is the case the match will satisfy an observer of normal colour vision.

Spectral luminosity curves as found by dichromats differ somewhat from those obtained by normal-sighted persons in that the maximum ordinate may be found towards the shorter or longer wave-lengths according to whether protanopia or deutanopia respectively is present.

The results obtained for luminosity are, however, easily misinterpreted as the maximum shifts (as previously noted), owing to the Purkinje phenomenon, with changes of intensity and with the parts of the retina used for observation. Consequently any spectral luminosity measurements ought to be made under exactly standardized conditions if the results are to be employed to assess defects of colour vision. The present writer well remembers being examined (as a student) by the late Professor Watson and being classed as a partial protanope. The defect was, however, traced later to a discoloration of one of the lenses in the colour-patch apparatus. Another

factor which may considerably affect the apparent nature of defects in colour vision is the variation in the yellow pigmentation of the macula. Persons with excessive or deficient pigmentation accompanying colour blindness are likely to find luminosity curves differing perceptibly from those given by ordinary types.

The late Lord Rayleigh drew attention to the existence of two well-marked classes amongst persons with colour vision somewhat less deficient than the above classes of dichromats. These two classes are distinguished in matching the colour of the sodium flame "D" light by mixing spectral red ($\lambda = .6708 \mu$) and spectral green ($.535 \mu$), some persons requiring more red, and some more green than the normal. These cases correspond apparently to partial protanopia and partial deuteranopia respectively.

It is also found that anomalous trichromats differ from the normal when matching the hue of a non-homogeneous light, such as that transmitted by a solution of potassium chromate, by selecting a spectral hue. It is characteristic that partial protanopes will select a more green, and partial deuteranopes a more red hue than the normal, but in both cases there are considerable ranges over which the match appears more or less satisfactory and the match which satisfies the normal lies generally at the extremes of these ranges.

Monochromatic vision (achromatopia) is comparatively rare in healthy eyes, but when found it is usually accompanied by other visual defects, such as indistinct central vision, photophobia, and nystagmus or involuntary movements of the eyes. It is noteworthy that although no differences of hue can be seen in the spectrum, the luminosity curve coincides very nearly with that of the normal. In tobacco and alcohol amblyopia central colour blindness or central *scotoma* may be induced as the result of excessive smoking or drinking, and this condition may be permanent. In such a case the vision is worst at the fovea.

In cases of disease the regions of indistinct or absent colour and form vision (*scotomata*) may be found elsewhere than at the centre.

The Colour-blind Standpoint.—Consider the education of a person who could distinguish a characteristic hue in the region round $.65 \mu$ and another in the region $.44 \mu$, which we name A and B respectively. He lives in sunlight and sees common objects. A robin has an "A" breast, but the leaves on his trees are almost grey, and only turn more "A" in the autumn. He sees little of

his other hue "B" in nature, except in flowers and a little in sky and sea. Then a teacher comes to him and tells him that the leaves are "green" and turn "yellow" in the autumn. He learns to associate particular saturations of "A" with the terms green, yellow, and red, but he will always be liable to confuse really unsaturated "A" with these appearances, although he does not in conversation appear to have much difficulty in distinguishing "green" and "red".

Another person has differing hue sensations excitable by spectral regions around $\cdot 54 \mu$ and $\cdot 44 \mu$, but finds the light beyond $\cdot 66 \mu$ impossible to see. He calls the longer wave-lengths hue "A", the other "B". As before, the robin has an "A" breast, but it is a very dull hue, almost invisible. He is liable to wear red garments in mistake for black, because they reflect only the long wave-lengths which are invisible to him, but otherwise the general character of the manner in which he *names* colours after due instruction will not be greatly different from the manner of naming employed by the first case that we studied. Intermediate regions of the spectrum are named grey.

It is naturally useless to inquire as to the fundamental nature of the sensations in the two cases, whether the one would perceive red *as we know it* and not see green, or whether the other would perceive green as we know it and not see red. Such speculation is interesting but hardly likely to lead to any result.

Edridge-Green, who uses the terms dichromic, trichromic, &c., for the perceiving of two, three, &c., very distinct hues in the spectrum, naturally explains colour blindness as a type of reversion to a former stage of colour evolution in which the colour-perceiving centres in the brain are imperfectly developed.

Colour Blindness on the Trichromatic Theory.—On the trichromatic theory the state of affairs would be largely represented for "green" and "red" blindness by the two imaginary cases discussed above. Referring to the "sensation" curves it will be seen that the red and green maxima are not far separated, and that consequently for many ordinary things the colour nomenclature of a red-blind person would be surprisingly similar to that of a green-blind person, although, when suitable tests are employed, erroneous naming is quickly detected.

Apart from cases such as these, there are many persons who might be described as "trichromatic". These have only a partial deficiency in one sensation. A partly red-blind person would have

a "shortened" spectrum, and would perceive two distinctive hues at the longer wave-length end, separated by an interval of grey from the characteristic short wave-length sensation. These colours would be *named* red, yellow or green, grey, and violet. Yellows and greens would be confused or misnamed in varying circumstances.

A partly green-blind person will have no shortening of the spectrum. The long wave-lengths give a distinct hue, which is modified by such green sensation as exists. There are then, as before, red, yellow, green, and an interval of grey, and then the characteristic short-wave sensation.

It is not difficult to see how the grey intervals arise from the point of view of a normal-sighted person. The green-blind person fails to appreciate green in the spectrum, consequently his "white" or "grey" corresponds to the hue of the spectral region where the stimulation of the remaining sensations, red and violet (now "complementaries"), are equal. To the normal eye this would produce purple, but possibly to the colour-blind eye the sensation would not be the one that we know by that name. In cases of red-blindness the "white" of the colour-blind person corresponds to a blue-green, and he sees "white" in the blue-green parts of the spectrum. In cases of partial red or green blindness, the white corresponds to a less saturated blue-green or purple respectively, and in cases of slight colour blindness no part of the spectrum may be called grey, although confusion may arise if colour patches are shown separately, especially in the parts of the yellow-green most resembling white to the normal eye.

Necessity for Tests of Colour Vision.—It is estimated that persons comprising more than 4 per cent of the population have defective colour vision, and it is therefore extremely necessary that persons engaged in occupations where the recognition of hue is of importance should be thoroughly tested. For clinical purposes tests which indicate defectiveness independently of any description of hues by the subject are desirable, but in testing seamen and others the colour education is of equal importance with the colour vision. It is *possible* that a person with little defect in colour vision might name hues wrongly through ignorance.

For work on railways and at sea, the distinction and correct naming of small red, green, and white or yellow sources are of greatest importance. The light from an oil lamp is very yellow,

and seen through a slight mist may become more red in hue. Consequently no person at all liable to confuse yellow with red or green should be passed for service as a driver, &c.

For an air pilot the tests should be the most exacting. Many lives may be lost through inability to select and distinguish the appearance of the ground where safe landings may be made; the bright green patch marking a bog, or the browner grass which might indicate better ground. Failure to distinguish correctly the dif-

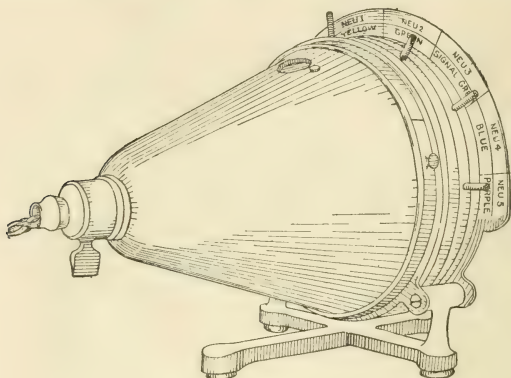


Fig. 64.—Edridge-Green Colour-perception Lantern

ferent hues of green is a marked characteristic of partial hue blindness.

The more subtle tests, which can be performed with the assistance of the colour-patch apparatus, will be of great service in cases such as these, where the "lantern" tests, to be described, or the other obvious and usual "first tests" give doubtful results.

Actual Tests for Colour Blindness.

1. **The Lantern Test** has been adopted by the British Admiralty. The method is simply to use various colour filters singly or together over a small illuminated aperture, the candidate being required to name the hues correctly. In Edridge-Green's lantern (fig. 64) the aperture can be varied in size, and three filters may be used simultaneously with a neutral or other modifying filter if desired. The coloured filters are carried in three rotating discs, each of

which contains clear, red A, red B, yellow, green, signal-green, blue, and purple filters. The diaphragm "is graduated in respect to three apertures to represent a $5\frac{1}{2}$ -in. railway signal bull's-eye at 600, 800, and 1000 yd. respectively, when the test is made at 20 ft." The tests are made when the eyes of the subject are "dark-adapted". The Williams lantern, very similar in principle, is widely used in America. Confusion of red with green or white (and conversely) necessitates rejection. Confusion of red or green with yellow points to the necessity of further examination.

It should be noted that tests made with small, brightly illuminated apertures of this kind tend to test the colour vision of the fovea most particularly, but they are not conclusive tests for the presence of central scotoma. A subject might be used to registering colour impressions away from the line of direct vision. A more decisive test for scotoma is:

2. **The Bead Test.**—A number of small beads of assorted colours in a box is given to the subject, who is asked to pick out those of a particular hue. In order to select a particular bead its image must be formed on the fovea, the only part of the retina which registers *form* with good definition. If central scotoma is present, hue and form vision may both be affected, and it is impossible to pick up the beads of the hue required.

Tests 1 and 2 will generally suffice to detect the presence of colour blindness. In the case of uncertainty when the more feeble hues are shown in the lantern it is desirable to proceed to quantitative tests. Before describing these, however, the Holmgren wool test and an allied test may be described, as they are still in use.

3. **The Holmgren Wool Test** (introduced in 1875) was so called after its originator, the Swedish physicist Holmgren. Wool makes a convenient test object. A large variety of colours may be obtained, and the colour of a skein looks very much the same from all positions. The method of the test is to require a subject to select, from a heap of about 125 small skeins of wool (red, orange, yellow-green, green, blue-green, blue, violet, purple, pink, brown, and grey in various shades and gradations of saturation), the particular skeins corresponding in *hue*, apart from mere brightness or darkness, to three particular test skeins.

1. A very light grass green.
2. A pink or rose colour.
3. A bright red.

These three tests are performed separately. We have seen that in complete protanopia or deuteranopia we have the spectrum consisting (broadly speaking) of two parts of differing hue separated by a grey or white. The green of the first skein corresponds to this most critical colour seen as grey by defective, green by normal-sighted persons. The tests can be most easily explained on the basis of the trichromatic theory.

If colour blindness is present there will be a tendency to select as matches for the first skein light fawns, greys, and (in more decided colour blindness) pinks or yellows; a red-blind person would see no red in a yellow or buff skein, and would therefore match these with the green, while a completely green-blind person would see no green in the test skein or in the other light skeins, and would, on the trichromatic theory, see many of the pale tints as varieties of light purple, corresponding to his "white".

The next test serves to determine the type of colour blindness more exactly. The completely red-blind subject sees the pink without the red component—therefore as a blue. Similarly he sees the mauves, violets, and blue or blue-green skeins as very similar in hue. A completely green-blind subject, who sees the blue and red portions of the spectrum strongly contrasting in colours, will not select colours containing much *blue* as matches for the test skein, but will select pale colours, white or neutral skeins. Estimates may be made of the completeness of colour blindness in this way.

The third and last skein will be matched by the completely red-blind subject with greens and browns darker than the red, and by the green-blind subject with scarlet, reds, and browns lighter than the red. This last test, however, only serves to give final confirmation of the presence of fairly complete colour blindness. Abney suggested the use of a dark brown instead of the scarlet as a test skein.

The wools should be guarded against soiling and fading, and should be renewed when necessary.

Experience has shown that in some cases gross colour blindness has been found in subjects who have been subjected to this test and passed, and on this account severe criticism has been directed against the Royal Society Committee, which approved the Holmgren test some years ago; but such criticism ignores the possibilities of careless examination or subsequently developed colour blindness. From the experience of the present writer there seems some evi-

dence to show that colour perception may be temporarily affected by health. It is well known that photometric measurements at least are greatly affected by physical conditions of health, and it seems that this matter is one deserving careful investigation.

Jennings has devised a method of conducting the Holmgren test in which the subject can record his own observations. The coloured worsteds are mounted on a board and are not handled. This method has been adopted by the Ophthalmic Section of the American Medical Association. For details see *Amer. Jour. Physiol. Optics*, Vol. I, No. 2.

4. **The Card Test.**—Different varieties are due to Edridge-Green and Nagel.

In the first, the subject is asked to read figures on a card formed by (say) a series of brown patches of irregular shapes amongst a series of green patches of similar brightness and size (or other more or less subtle colour contrasts). Nagel's test employs cards having coloured discs arranged in a circle, some cards having discs varying in colour or shade; the subject is asked to select those in which confusion colours have been introduced.

These tests are very useful where a handy test, independent of much apparatus, is required.

5. **The Colour-patch Test.**¹—This is conveniently performed with the colour-patch apparatus. Patches of pure spectral colours are thrown on a small white square or "dot", and the subject is asked to name them. Deficiency of red sensation or shortening of the spectrum is very easily found in this manner, and the naming of the yellow-green (or "brightest light") part of the spectrum after viewing other colours gives a very good test of any irregularity.

A test of colour vision should include the lantern or colour patch test, the test No. 2 (above), and one of the other tests.

There are numerous possibilities for qualitative tests of the above descriptions, but in the opinion of the present writer it is most important that, when a doubtful case is dealt with, the final tests should be strictly quantitative. Very grave injustice may be done to men whose slight deficiency in colour sense causes them to stumble in some of the more difficult tests, and yet who would be perfectly able to recognize red, yellow, and green lights under

¹ Similar tests can also be performed with Edridge-Green's spectrometer, an instrument somewhat similar to Hilger's Constant Deviation Spectroscope, but adapted to give colour patches of definite wave-lengths indicated by the "drum".

any practical conditions. Here we may note that the use of quantitative¹ tests does not involve the final acceptance of any particular theory as fundamental truth, even though some tests *may* recognize and use the theory as a convenient method of describing the well-recognized laws of colour-mixing phenomena.

6. **Measurement of Sensation Deficiency.** — A colour-blind subject M makes brightness matches of spectrum colours with white by varying the latter, while N with normal sight repeats the experiment. To N the luminosity of the white is composed of the "luminosity of red, green, and blue sensations" in the proportions of 580, 250, and 3.

A particular spectrum colour being chosen, M and N make brightness measurements in turn, and find that amounts a and b of white are necessary for their matches respectively.

Let the sensation-efficiency factors for M in red and green be x and y respectively. The blue sensation may be assumed normal in the majority of cases. We thus obtain two "luminosity" equations to represent the matches (assuming r , g , and b to be the normal sensation luminosities for the spectrum colour).

$$(1) \quad xr + yg + b = (580x + 250y + 3)a$$

$$(2) \quad r + g + b = (580 + 250 + 3)b.$$

Since the brightness of the blue sensation is very small, the equations may be combined to give approximately

$$\frac{xr + yg}{r + g} = \frac{(7x + 3y)a}{10b}.$$

r and g are known (see the sensation-luminosity curves), and a and b are measured. This leaves x and y as unknowns.

The measurement may, however, be performed for a spectrum colour of wave-length greater than $.66 \mu$. Then $g = 0$, and the equation becomes

$$x = a \frac{(7x + 3y)}{10b}.$$

This will fix the amount of red blindness if $y = 1$.

¹ For a description of some suitable quantitative tests Abney's *Researches in Colour Vision* may be consulted. The luminosity test is not suitable for persons untrained in observation.

If we have a green-blind subject, with no red sensation deficiency ($x = 1$), the equation becomes

$$\frac{r + yg}{r + g} = \frac{(7 + 3y)a}{10b},$$

which can at once be solved for y .

Two equations would be necessary if neither x nor $y = 1$. Therefore it will be seen that from luminosity determinations at a few places in the spectrum it should be possible to determine the factors representing colour sensations.

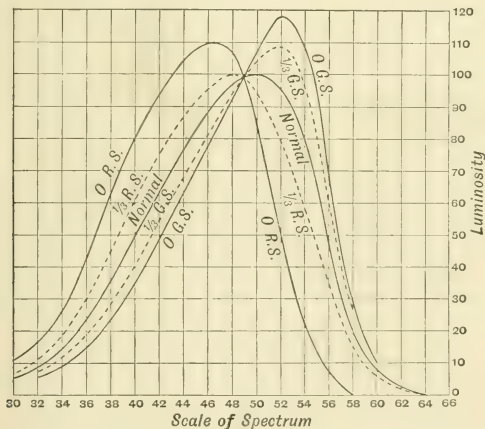


Fig. 65.—Luminosities compared with White for different degrees of Colour Blindness

7. Luminosity Test.—Watson developed a method¹ of determining the colour sensation deficiency from the luminosity curve of the spectrum taken, by means of a flicker method, by the colour-blind subject. The luminositities *as compared with white* for different degrees of colour blindness are shown in fig. 65, these curves being theoretically derived from the sensation luminosity values. The experimental luminosity curve for a particular subject should be plotted on the same diagram to determine which of the theoretical curves most nearly fits it. The simplicity of the method is some-

¹ *Proc. Roy. Soc., A*, LXXXVIII, p. 410, 1913.

what vitiated by the difficulty of allowing for variations of macular pigmentation.

8. Anomalous Matches.—At the end of the chapter on colour vision certain weaknesses in the trichromatic theory were mentioned, and similar difficulties are found in explaining all the observed facts of colour blindness. For example, if a normal person makes a match by means of spectral red and green to imitate a yellow (say that produced by passing white light through a solution of potassium chromate), the matching would be explained (on the theory) by saying that the yellow stimulated the red and green *sensations* in the same proportion as does the mixture. If then colour blindness is explicable by supposing a partial lack of response of a particular sensation, the match ought still to be perfect even to a partly colour-blind person, but this is not always the case.

Colour blindness may differ then from the artificial blindness induced by fatigue, which does not upset the match to which reference is made.

In order to explain these anomalies it is necessary to suppose that in some cases a sensation curve may be shifted or changed in shape relatively to the wave-length scale, as distinct from the simple alteration of its ordinates in a constant ratio; and in this connection it is interesting to note that Houston,¹ experimenting in a novel manner, comes to the conclusion that some cases, previously considered to manifest colour *deficiency*, show rather a colour *alteration*. Their conditions for sensitiveness to changes of hue in colour mixing differ from the normal. Cases of shifting of a hue sensation have been examined by Abney and Watson.²

Nagel's anomaloscope is a simple instrument similar to a direct-vision spectroscope, in which a yellow may be matched by a mixture of red and green. The brightness of the yellow and the ratio of red to green are indicated by the readings on two micrometer heads. The numerical divergences from the normal readings are taken as arbitrary measures of the "anomaly".

¹ *Proc. Roy. Soc. Ed.*, Vol. XLII, Part 1, p. 75, 1922.

² *Proc. Roy. Soc. Lond.*, 28th May, 1914.

PART III

CHAPTER XI

Colour Printing

Probably the oldest process of colour printing is that practised for many centuries down to the present time by the Chinese and Japanese, in which a number of wood blocks are cut, each having in relief the portions representing the colour to be printed. The blocks are brushed over with colour, formed of pigments mixed with rice paste to give them body; paper is laid on and rubbed into contact with the relief surface by means of a flat pad. Any colour lying in the hollows between the relieved parts is not taken up, because it does not reach the paper. When the first printed colour is dry the paper is applied to a second block brushed over with another colour, and so receives a second colour. These imprints are followed by a third and sometimes more, until the composite coloured print is secured. Extremely artistic results are produced by this simple means.

Block printing was introduced into Europe in mediæval times, and was at first used for the printing of books, mostly in black, with the occasional introduction of a coloured initial letter. The primitive means employed by the Chinese and Japanese for colouring and taking the impression was improved on by applying the colour in the form of an oily paste (printing ink) with a leather pad, which was dabbed on to the surface of the relief, and the impression was taken with a screw press.

With the introduction of movable type for the text, block printing was retained only for the production of the coloured initials and illustrations, and attempts were made to copy the colour decoration which embellished the text in the earliest printed books.

Gradually colour printing progressed from initials to border designs, and eventually to pictures. Sometimes the colours were partly printed and partly applied by stencils. As wood-engraving improved more ambitious attempts were made, but all these early efforts were confined to colouring the outlines of pictures by solid masses of colour, without any effort at blending by printing one colour over another.

Even when engraving on metal was introduced, the same method was practised, the prints being coloured by the method known as *chiaroscuro*, in which the background was printed with a tint or tints to give effects of light and shade that could not be produced by mere outlines. Sometimes colour effects were obtained by printing on coloured paper.

The idea of printing lines, stipple dots, or grain to produce lighter shades of the colour than the solid patches of full strength does not appear to have been realized until some time about the middle of the sixteenth century, when it was practised to a limited extent by some Dutch engravers, contemporary with Rembrandt; but apparently the plates were inked in different parts with various colours, so as to take all the colours at one impression.

Colour printing from plates was improved upon by producing as many plates as the required colours and printing from them successively in register. In the case of plates engraved in line for black printing—in etchings, for example—the effect of the engraved line was reproduced in the colour print, and gradually engravers and printers began to see possibilities of obtaining a greater range of effects in this way.

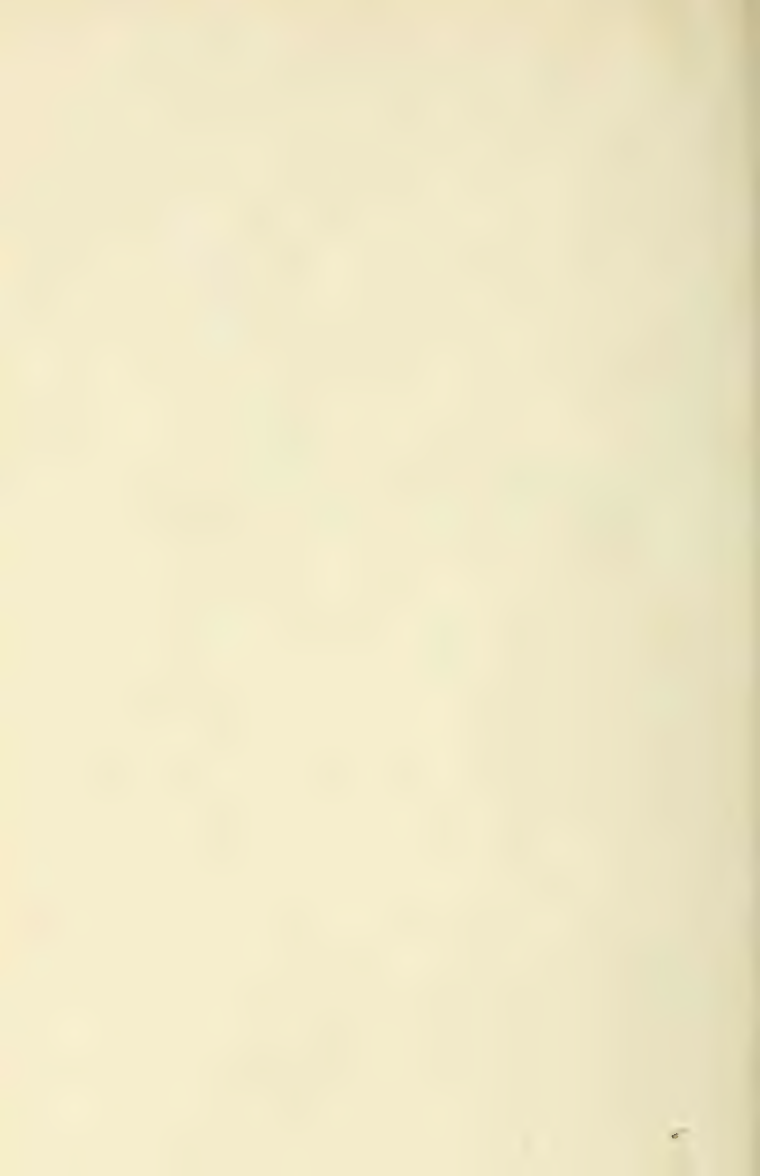
From the colour printer's point of view the most important achievement of the early part of the eighteenth century (some thirty years after Newton had published his researches on the spectrum) was the invention by James Christopher le Blon of his three-colour process, which was the foundation of the modern process of three-colour printing. Le Blon had not the use of the camera, but his effects were produced on identically the same fundamental principles as are those of the present-day processes. He was the first to apply to colour printing the idea that there are three colour sensations, which can be represented by red, blue, and yellow. The medium he selected for the purpose of demonstrating the correctness of his theory was the engraving method known as mezzotint. This produces on the copper plate a stipple, which can be lightened or darkened by the processes of the engraver so





PRINTING

erposed to form the colour print



as to produce a light or dark tint. Consequently when the plate is inked with suitable colours, light, medium, or dark shades of colour can be printed; and by superposing one shade over another, combinations of colours are produced.

The invention of lithography gave the printer a new means of colour printing, which was developed immensely under the name of chromo-lithography. It was found that the stone, which is used for printing, could be grained so that when drawn on with crayons a stipple effect was produced, and a great range of tones obtained, from solid colour (by filling up the space between the grain points), to the lightest shades (by leaving the grain open, so that only the upstanding grain points were printed). By successive printings with different colours on the same sheet an infinite variety of combinations of colours could be obtained. Of course the success of the result was due to the skill of the artists who worked the drawings on the stones. At the present day chromo-lithography in that form has been superseded by processes of photo-mechanical selection, aided by subsequent hand work.

Collotype was one of the earliest photo-mechanical processes with which it was sought to supersede the work of the artist. In this process the grain is produced by a chemical reticulation of a gelatine surface. The light and shade of the photographic negative, under which the collotype plate is exposed, is reproduced by a grain which prints more or less heavily, according to the intensity of the light which has acted on it through the tones of the negative. The plate can be inked and printed from in the same manner as the lithographic stone. Early workers in the process conceived that if three plates were prepared from colour-selective negatives, it would be possible to print from these plates superposed impressions which would reproduce any coloured picture. The process was found too uncertain, and the photographic block processes superseded it for commercial printing until recent times, when there has been a revival of the idea of collotype colour printing. With better means and wider experience it has been possible to produce some very fine results by this process. In some cases the black or monochrome key plate is printed by collotype, and the colours printed on it by lithography.

Undoubtedly the greatest development of colour printing has resulted from the half-tone block process, and the application to it of the three-colour photography. The half-tone block is made by placing in front of the sensitive photographic plate a screen,

which consists of a cross-hatching of black lines ruled on glass. Exposure through this has the effect of breaking up the image into dots, the character of which may be seen by examining with a magnifying glass half-tone prints, such as may be found in any illustrated book or periodical. It will be observed that these dots vary in size in proportion to the light and shade of the picture. In the highest lights the dots are the merest pin-points, and as the middle tones are approached they get larger, until they blend together and finally produce a solid mass in the deepest shadows. The dots being very fine, of the order usually of $\frac{1}{32}$ in. in well-printed work, the eye fails to observe the discontinuity of the tones, and sees only an effect of light and shade, such as is obtained in a photograph. In coarsely printed work, such as in daily newspapers, the dots are more visible, but the relative light and shade effect is the same.

The enlargement of the dot, without producing discontinuity of the tones, is carried to a greater degree in poster work, and so long as the picture is viewed from a distance the effect is not unpleasant.

The negative produced through the screen may be regarded as a stencil, through which the light acts on the sensitive surface placed under it. The transparent openings in the negative correspond to the dots which are to be printed. To obtain these dots in relief on the printing block a piece of copper or zinc is highly polished and coated with a solution, usually consisting of glue or albumen mixed with a bichromate salt. This latter makes the film sensitive to light, and the effect is that those parts of the plate which are under the transparent openings of the negative are hardened, as the result of a tanning action which takes place. The plate is then soaked and rinsed with water to dissolve away the parts which have not been so affected, and the result is to leave an image of the picture in dots on the metal surface. These dots are further hardened by baking over the heat of a gas stove, which has the effect of giving them an enamel-like hardness. They are then in a condition to resist an etching mordant, such as perchloride of iron for copper, or nitric acid for zinc. The mordant, therefore, attacks the bare metal between the dots, leaving hollows so that the dots stand up in relief like little pyramids, enabling their summits to be inked, whilst the hollow spaces are kept clear. When the plate is mounted on a block of wood to bring it up to the height of printing type it can be printed from, along with the type, by inking the surface and pressing paper into contact with it.

Half-tone negatives are also used for making lithographic printing plates. In this case the dots are not in relief, but the ink is prevented from reaching the parts between the dots by keeping the plate damp, the moisture repelling the ink.

Not long after the invention of the half-tone process attempts were made to apply it to colour work. At first the skill of the artist-etcher was relied on to select the parts of the negatives which represent the colours, as in the case of chromo-lithography, but with the progress which was being simultaneously made in the application of the three-colour theory to photography it was soon seen that, if three half-tone negatives could be made with selective colour-filters interposed in the path of the light rays, it would be possible to produce almost mechanically three blocks, and, by printing from these successively in register on the same sheet of paper in yellow, red, and blue respectively, it would be possible to produce colour prints which would approximate quite closely to the colours of the original picture.

Success was not attained at first, nor for a long time, because the workers proceeded on the old chromo-lithographic plan of merely superposing the colour tones without taking into account the effect of irregular superposition of the dots. Thus some dots were buried up completely whilst others overlapped more or less, and as the inks were not transparent the colour effects were promiscuous, and *moiré* patterns were formed by the overlapping dots. It was then discovered that by placing the ruled screen for the respective colours at different angles of inclination relative to the order of the picture a much more perfect result could be obtained, as the dots were then displaced in each block so that they formed a pattern, invisible to the naked eye, in which they were rather in juxtaposition than in superposition. Colour mixture was thus effected through the eye uniting two or three dots to form the combination colours, yellow and blue dots side by side, for instance, giving the effect of green.

By securing inks which were purer and more transparent, and by cutting out or lightening portions of the blocks by hand work, it was found possible greatly to improve the results; but the most progress was made when improvements in the colour filters and in the colour-sensitive photographic plates were made. The process has now been brought to a high degree of perfection, but there is still scope for further improvement in the photographic part of the process, so as to eliminate more of the hand work, which is still

resorted to in order to correct the imperfection of colour rendering by the camera.

The deficiencies of the process lie partly in the colour filters and partly in the photographic plates. In both respects much has been done to bring these as near to perfection as the means available will allow, but fresh discoveries of dyes may bring about improvements in the filters and plates, whilst possibly something better than the gelatine dry plate for colour photography may be found.

In the early days of three-colour research it was found that the method of preparing plates with collodion emulsion was better suited for introducing the colour-sensitive dyes than the gelatine plates; but the greater convenience of the latter has outweighed its disadvantages.

The nature of the illumination of the original has a considerable influence on the results. In commercial work the electric arc light is invariably used, and this is too often deficient in light of certain wave-lengths whilst yielding an excess of others. As the original can only reflect light of such wave-lengths as fall upon it, there would seem to be an opening for methods of illuminating the original at each exposure with light of only the colour wanted for that exposure if this were possible. Attempts have been made by using coloured-flame carbons, or white-flame carbons with colour screens interposed, to illuminate the original with suitable light, but so far the only method which has come extensively into use is that of using the open arc with white-flame carbons.

Recently it has been proposed to illuminate with the actual light of the required parts of the spectrum, projected from a special apparatus which will transmit only the rays desired.

Another method consists in taking a negative from the picture through the chosen colour filter and projecting the image of this negative back on to the picture, so that it exactly fits. The colour filter with which the negative was taken is placed in the path of the rays, so that the transparent parts of the negative project coloured light. This intensifies the illumination of corresponding parts of the picture, with the effect, it is claimed, of improving the colour rendering on the half-tone negative finally taken. There seems to be a field for experiment in this direction.

One drawback in using the half-tone process for colour printing is that the dots are all over the picture, and there can be no clear lights, so that the whole image is rendered in a lowered tone. This has to be corrected by much hand work (which can only be directed

to lightening the dots or removing them entirely), making the printing of the block difficult.

The ink-rollers are apt to dip into hollows (corresponding to the lights), so that the paper becomes smeared in these places; and the printing is apt to produce hard smudgy edges where the dots finish. In lithography these drawbacks do not occur, as the ink from the rollers is prevented from resting on the light spaces by the repellant action of the moisture on the plate, and the paper, though in contact with the whole surface, is not liable to smudging. Thus in lithography it is possible to use what is called the "high light" process, when the dots are blocked out in the high lights, so that these parts come out white in the prints. Here, too, it is possible to leave out masses of colour, so that the other colours may print solid, or in combinations of two colours only—a great gain to the colour rendering.

It may be mentioned that it is not necessary in all cases to use a ruled cross-line screen to produce the dot system. A grained screen with irregularly shaped grain points may be used in front of the sensitive plate, and a pleasing effect produced which is especially suitable for lithography.

The paper used for colour printing has a great influence on the results. For the half-tone process it is necessary to use a highly glazed paper coated with a chalky material, in order to secure clean and sharp printing of the dots. This imposes considerable limitations on the effects to be obtained. On the other hand, by means of what is known as offset lithography, practically any surface can be printed on—even rough papers such as are used for water-colour painting—and it is thus possible to obtain effects more closely approximating to the original picture. In offset printing the image is first impressed on a rubber sheet and then in turn transferred to the paper, so that any inequalities in the surface of the latter are embedded in the rubber during the impression.

With regard to inks for three-colour printing, it is to be noted that the choice lies between pigments that are permanent, or fairly so, and those which are non-permanent. The latter give the nearest approach to theoretical requirements, but can only be used in book illustrations or for work which is not likely to be exposed too much to light. In practice the permanent inks are mostly used, and correction made in the blocks to suit them. The chief permanent inks are cadmium yellow, madder lake, and Prussian blue; whilst the non-permanent inks are a light chrome yellow, rose lake, and

a greenish peacock blue. Ink-makers have different standards (see Chapter VI, Addendum), and it is usually left to the block-maker to produce his blocks to suit certain inks.

The order of printing the colours is important. The usual practice is to print in the order: yellow, red, blue. If there is a fourth printing of black or grey it is done last. An attempt has been made to print in the reverse order (blue, red, yellow), but the result was not so good, nor could it be, seeing that the yellow is a relatively opaque colour. The last colour printed is always predominant, and this has to be allowed for in making the block. Otherwise there may be an excess of blue, giving an unpleasant effect.

It is often sought to correct the defects of the three-colour process by the addition of a fourth printing, usually in black ink, the block being specially made to contain just those portions of the picture which require strengthening. In lithography five and even more colours are often used—for instance, light and dark reds and blues, and a grey neutral tint, the last because it is thought the three-colour process is particularly deficient in rendering greys.

An interesting attempt to found a four-colour system was the complementary colour process of Zander, who used red, yellow, green, and blue. The hues of these four fundamental (or monochromatic) colours may in popular terms be described as magenta red, lemon yellow, emerald green, and ultramarine blue. The inventor claimed that practically the whole range of spectrum colours could be produced by it, besides extra spectral purples, dense black, and homogeneous greys. The results, however, were not convincing.

There is another process of printing which produces beautiful results in monochrome, and is being tried for colour work, viz. photography. It yields the richest results, because the deposit of ink is proportional to the light and shade of the picture. It would therefore seem to be ideal for rendering colour shades. Some very fine results have been produced; but at the time of writing it is too early to predict the future of this process. At present, either through imperfect inks or inherent difficulties of the process, the results are uncertain in quality.

It should be noted that in all processes of colour printing the ink first printed should be dry before the second colour is applied. Otherwise quite irregular results will be obtained. Attempts have been made to do "simultaneous" colour printing, that is to say,

impressions of the different colours following immediately, but they have only produced crude results, except where the blocks or plates have been made specially for the process so as to print in mosaic fashion, without the superposition of any more or less solid colours. Coloured inks have been "doctored" so as to dry quickly, or sufficiently so to prevent the successive colours from mixing; but this has not improved the colours, and this expedient is now abandoned.

It may be remarked here that pleasing colour effects have been produced by printing in *two* colours, using a greenish blue and a brown, or a bluish grey with a red. Another way has been to print in red and blue on a lemon-yellow paper.

Colour printers have often attempted to give a more realistic appearance to their reproductions of paintings by embossing the prints to give the effect of the canvas texture and the impasto or brush-marks of the original work; also in some cases varnishing the surface to increase the effectiveness. Similarly, paper has been embossed with the texture of water-colour drawing-papers.

CHAPTER XII

Photography in Colours

By most people, and particularly by those unacquainted with the details of photographic processes, it is assumed that a colour photograph is a result produced by placing in the photographic camera a plate which is sensitive to all the colours of nature, and obtaining in some way on the plate either the representation of the colours, or such a rendering of them on the negative as will enable a print in colours to be produced.

As a matter of fact no such easy and straightforward process has yet been discovered. No sensitive salt or other material has so far been found that is capable, on exposure to coloured light, of yielding a product which will possess the colour of the light which falls upon it, or which when applied to paper and exposed to light passing through the negative will be converted into the colours of the rays which fell on the plate on which the negative was made.

Experiments certainly have been made to show that a silver sub-chloride may, under certain conditions, be made to reflect light similar in composition to that which caused the formation of this sub-chloride, but these results have not been carried beyond the stages of laboratory research.

The process of the late Professor Lippmann came very near to achieving the ideal of colour photography, for he was able to secure on the sensitive plate placed in the photographic camera the actual colours of the light which had fallen on the plate. Starting with the theory first expounded by Zenker of stationary light-waves in the phenomena of interference, he reasoned that if he could obtain within the thickness of the photographic film a record of colour-waves in the form of a series of extremely thin layers of silver deposit, separated by equally thin layers of no deposit—merely the clear layers of gelatine—he would expect to find that, when these layers were looked at in light falling on them at a suitable angle, they would show colours just as a soap-bubble does, owing to the

light reflected from one layer interfering with that reflected from the next.

The means by which Lippmann achieved this result were extremely ingenious. Taking the fact that whenever light is reflected back upon itself, as from the surface of a mirror, interference takes place, though not visible to our eyes, he assumed that if he placed a mirror behind the sensitive plate in the camera the light coming through the lens and passing through the sensitive film would, when it fell on the reflecting surface, be sent back upon itself. The effect of this would be that where the reflected ray and the incident ray reinforced one another, at points where the crests of both their waves coincided, there would be the greatest amount of light-action, and where they opposed one another there would be darkness, and consequently no photographic action. The result would be that the film would consist of light and dark layers separated by distances proportional to the wave-lengths. For example, the parts of the film thus acted upon, corresponding to the red parts in the original object, being formed by red rays, would have their layers farther apart than those corresponding to the violet parts and formed by the shorter waves. The fact that such layers actually existed was proved by cutting such a film into sections and reproducing it by photomicrography so as to show the layers distinctly. Looked at by transmitted light the plates produced by Professor Lippmann have no definite colour; they are grey like an ordinary photographic plate, but with a reddish tinge. When, however, the surface is examined under light falling at a suitable angle, and with a black background under the plate, the natural colours are seen most brilliantly. The writer has in his possession two plates produced by this process—one by Professor Lippmann himself—which are very brilliant and natural. One is a spectrum of sunlight, and the other a reproduction of an old coloured print.

The Lippmann process, beautiful and perfect as it is, has never come into general use in photography on account of its inherent difficulties. Colour-sensitive plates of a special character have to be made, as they are not obtainable commercially, and a special dark slide is required to hold liquid mercury at the back of the sensitive plate and so form the mirror. Exposures are comparatively long and the results somewhat uncertain.

Another process of great scientific interest, which may yet yield the long-sought-for secret of colour photography, is that based on the researches of Wiener. His theory is thus explained: A light-

sensitive substance can only be altered by those coloured rays which this substance absorbs; red light will therefore have no influence on a red body, nor will yellow or green rays produce any effect on a green-coloured substance. If, therefore, a light-sensitive substance is discoloured through the influence of light, this substance will, when exposed to red, yellow, or blue light, continue to alter until it is of a red, yellow, or blue colour.

To apply this theory practically, papers are coated with fugitive red, yellow, and blue dyes of the coal-tar group, one layer over the other, producing a relatively black coating, as seen on the final surface. When such paper is exposed under a coloured transparency, correspondingly coloured prints are obtained, some colours fading under the action of the light, while others come up in full strength because unaffected by the exposure. The exposures are very long and the results uncertain.

The failure to obtain, with any easy method, reliable results in colour photography by direct-light action has led experimenters to turn their thoughts to the production of coloured pictures by indirect means.

Reasoning on the basis of the three-colour theory of vision (see Chapter IX, *Trichromatic Theory*), the early experimenters thought that since all colours of the spectrum can be excited in the eye by means of rays of the three primary colours, in suitable proportions, then it will be sufficient, if three coloured pictures, each in one of the primary colours, can be exactly superposed simultaneously on the retina, to produce in combination a good imitation of the object pictured in its natural colours. They argued that if three photographs of the same object could be taken on three separate plates, one in each of the primary colours, and the combined image subsequently constituted by projecting from a lantern, or by printing them one over another on the same sheet of paper, we ought to get a picture giving a fair imitation of the colours of nature.

Though the theoretical basis is thoroughly sound, the difficulties of putting the theory into practice have proved very great, and even now the problem cannot be regarded as fully solved. To begin with, it was found that the ordinary photographic plate was more sensitive to the blue and violet than to the green, yellow, orange, and red parts of the spectrum. This obstacle has been overcome by making the photographic plates more sensitive to the last-named colours by impregnating the sensitive film with dyes, so chosen as to influence the distribution over the spectrum of colour sensitive-

ness in the photographic plate. It is now possible to obtain "panchromatic" plates, which are practically sensitive to the whole range of the spectrum.

It was then sought to discover colour screens, or filters as they are now generally called, which would absorb certain rays more or less completely, so that only light of the particular colour desired should reach the plate at each exposure. This was not so easy as it seemed; for, though scientists were able to define just the three respective rays which should be passed, it was very difficult to find suitable coloured glasses or dyes to form coloured films to pass these rays and no others. It is now quite understood that the light filters for taking the images should be red, green, and blue-violet, but there is room for considerable variations in these colours according to the materials used for producing them. Careful spectroscopic tests will reveal what are the best, but the highest attainment so far is but an approximation to the ideal requirement.

Having obtained the colour-sensitive plates and the colour filters, it might be assumed that it was an easy matter to put them in the camera and obtain by three successive exposures the required negatives. Further difficulties, however, arise in the different amounts of exposure required for each colour, so that factors had to be determined for each kind of plates and filters, in order that negatives of equal densities are obtained. Then again there is the difficulty of obtaining images of equal size, due to defects of achromatism in the lenses used, and separate focusing for each colour is not practicable. In modern lenses of the highest quality this defect has been remedied, leaving only such faults as may be due to lack of optical qualities in the colour filters or want of accuracy in the camera.

Obviously another difficulty was the possibility of the light intensity changing between the exposures, and there might also be movement in the objects whilst they were being photographed; even such unobserved movements as the drooping of a flower or the curling of a leaf would cause those parts of the image to take different positions on the three plates, so that they would not register when the images were superposed.

Inventors accordingly set to work to devise cameras which would take the three exposures simultaneously, or with such a slight difference between the exposures of the three images that any movement would be unlikely or at least negligible. A great variety of such instruments has been made, and immense in-

genuity has been displayed in overcoming the difficulties of the problem. In many cases use has been made of mirrors or prisms to split up the image from a single lens into three separate images, each with a colour filter in the path of the rays. In more than one instance the lens has been divided into three sectors each forming a separate image, whilst others use three separate lenses, and form separate compartments in the camera for each image. The last method has been found defective by introducing differences of perspective, whilst the drawback to the use of mirrors and prisms is the loss of light involving impaired definition; this equally applies to the system of dividing up the lens.

Another group of inventors have essayed to produce two of the images by placing the sensitive surfaces together, so that the light passes through the first plate to that at the back (making the latter the one that needs the least exposure), whilst the third image is obtained by reflection from a transparent mirror placed at 45° to the incident ray.

One of the most promising ideas tried was to place the three sensitive surfaces behind each other, with the colour filters between like the pages of a book, but unfortunately it has not been found possible to provide the sensitive plates and filters which would enable this to be successfully accomplished.

A camera recently invented seems to come nearest to the realization of practical requirements. It contains one lens, behind which is a rotating disc with openings filled with the colour filters. Each opening can be closed down by means of an iris shutter, so as to admit just the amount of light called for by the exposure factors of the filters. The plates are held in a magazine at the back, and the exposures are made by pressing a pneumatic bulb, which releases the shutter to make the exposure, then changes the colour-filter and the plate, the second and third exposure being made in the same way by repeated pressing of the bulb. Negatives of identical size, sharpness, and density have been made with this camera.

For reproduction of coloured pictures, or for photographing inanimate objects in the studio, it is usual to make the three exposures successively in an ordinary copying camera, the filters and plates being changed after each exposure. This is found quite practical for making negatives for process blocks or for photolithography.

The three negatives having been obtained by one means or

another, the next problem is to make the colour prints. We have indicated in the previous chapter how they are applied to the production of plates or blocks for colour printing, but the amateur or professional photographer wants to produce the prints himself on paper by some such ready means as he now uses for producing ordinary photographs.

So far no such direct and simple means exists for producing colour prints. There are a variety of processes, but all involve a greater number of operations than the ordinary processes and require greater care. One of the most popular methods has been to make colour transparencies on thin films and to superpose these films in exact register. It is possible so to prepare the film that, after a print is made on it from the colour negative, it can be dyed to the appropriate colour—the complementary of the colour used for the colour filter in taking the image. If this operation is performed for the three prints, it is easy to superpose them and get a coloured picture, which will be more or less accurate according to the success of the different operations. Lantern slides have been made very well by this method.

Another way which enables prints to be made on paper is to print the image on to a gelatine surface, dye it, and while it is wet take off an impression on a suitably coated paper, very much in the same way as is done in copying letters by the old "Hektograph" gelatine pad. If a second print is superposed on the first and a third print on the second, taking care to get register, some reasonably good results are obtained. This process has been successfully developed under the name of *Pinachrome*.

Methods have also been devised of developing bromide of silver images and toning them to the desired colours. In some cases it has been found possible to treat the print in three successive solutions without affecting the previously developed image and so get a pleasing coloured image, but it can hardly be regarded as colour photography.

A popular way of obtaining colour prints is by means of the carbon process. Red, yellow, and blue tissue is obtainable, and after each kind has been printed under the respective negatives the prints are developed and transferred one over the other in register, thus obtaining a coloured print in pigments. The results are much richer than those obtained by dyeing.

A modification of the carbon process, known as *Ozotype*, is capable of producing excellent coloured prints. The image is

printed on to a bromide of silver paper, and after being developed the print is attached to a piece of wet carbon tissue. The bromide of silver combines with the bichromate in the carbon tissue to form an image of the same colour as the tissue. This can be developed, and after it has been dried and coated with a waterproofing medium, a further print of the second colour transferred on to it, the third following in the same way.

None of these processes of making colour prints has come into extensive use, the operations proving too difficult and uncertain for the average photographer, and only a few enthusiasts have succeeded in producing really good results. A reliable and easy process has yet to be discovered.¹

There is another method of producing photographs in colour which has been extensively employed. It depends on the principle of juxtaposition of colours in dots or lines. Just as the colour printer seeks to obtain effects by means of dots or lines, so the inventors of what are called screen-plate processes seek to translate colour in a similar way in the photographs. Instead of a colour filter of uniform tint for each colour being employed, a plate ruled with coloured lines is used, these lines being alternately red, green, and blue-violet, of equal width and lying close together; the groups of these three are repeated over the whole surface of the plate. This screen is placed in front of the sensitive plate and in close contact with it when taking the photograph of a coloured object. Let us suppose this object is red; then the red light reflected from it will only pass through the red lines of the screen-plate, as it will be stopped by the blue and green lines. When the plate is devel-

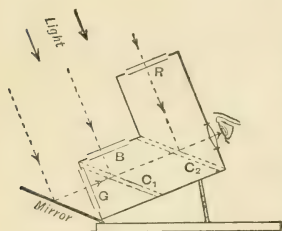


Fig. 66.—The Ives Kromskop

¹ It is possible, however, to print transparencies from the three negatives made as described above. By means of the simple optical device of the Photochromoscope, or Kromskop, of Ives (fig. 66), these three transparencies, illuminated respectively by red, green, and blue-violet light, are seen in apparent coincidence. In the figure the letters R, B, and G indicate the positions of the red, blue, and green transparencies with their corresponding colour filters. The images of R and B are brought into coincidence with G by means of the plain-glass reflectors C_1 and C_2 . Each transparency is a stereoscopic pair. Ives

pointed out that the spectral transmission of the colour filters (both for taking and viewing) should correspond as nearly as possible to the corresponding primary sensation curves. M.

oped the image will be found to consist of black lines corresponding to the red lines of the screen, these black lines being separated by a transparent space equal to the width of two black lines. This transparent space corresponds to the width of the green and violet lines on the screen. If a positive plate is made from this negative we shall get the opposite effect—black lines of twice the width of the transparent line. If we place the screen-plate with which the image was made in contact with the positive, adjusting it so that the red lines of the screen-plate exactly fit over the transparent opening, we shall see only a series of red lines, because the blue and violet ones are cut out by the opacity of the black lines. In the same way, if the object had reflected green rays only, we should see only green lines, or if blue only there would be blue lines. By holding the positive and screen-plate joined together, and looking through them at a sufficient distance (say arm's length) from the eye, the line effect disappears and we see a uniform tint.

If such a screen-plate is used for photographing an object containing several colours, they will be picked out by the coloured lines, all the red parts going through the red lines, the green parts through the green lines, and the blue parts through the blue-violet lines. Should there be combination colours, part will go through one of the coloured lines and part through the others, or portions may go through all three, the result being faithfully recorded in the negative by varying degrees of opacity, so that when the positive is applied to the screen-plate for viewing, these varying opacities will let through varying amounts of colour, which will be blended by the eye into a harmonious picture.

Such in brief outline is the process of Professor Joly of Dublin, and this was the forerunner of a number of the so-called screen-plate processes. The modified methods consist simply in the pattern of the screen. For instance, in the Thames plate process the colour elements were little squares of colour, something like a chessboard on a miniature scale, and in the Paget, the Dufay, and the Omnicolor the screens are similar, but produced and arranged in a slightly different manner. Fig. 67 shows the arrangement in three cases.

In the Lumière Autochrome process the screen-plate is quite differently arranged, and the procedure is also quite in another manner. The coloured elements consist of granules of starch, dyed in three portions to a red, green, and blue-violet colour, mixed and spread over the plate, to which they are made to adhere

closely. The interstices between the granules are filled with black powder, and, by suitable treatment in the course of manufacture, the whole layer of colour is made homogeneous. This plate is coated with a sensitive emulsion over the screen layer, so that it

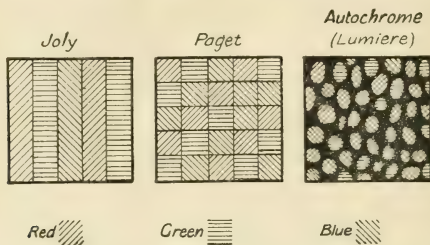


Fig. 67.—Taking Screens for Colour Photography (greatly magnified)

becomes to outward appearance like a photographic dry plate; it is put into the camera with its uncoated surface towards the lens, so that the light has to pass through the coloured granulation before reaching the sensitive coating. The effect is the same as we have

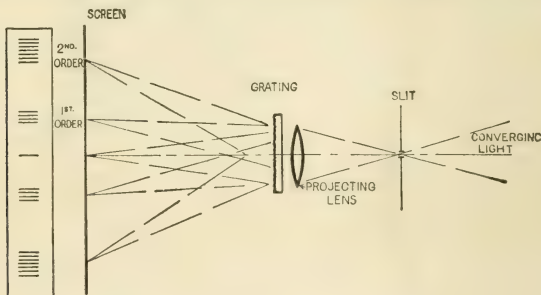


Fig. 68.—Production of Diffraction Image by a Grating

described in the Joly process, and the result is a negative. By chemical treatment the image is made positive, and then, on looking through the plate against the light, we see the photograph in wonderfully vivid colouring. By this process almost every conceivable kind of coloured subject has been produced with great faithfulness—even portraits from life—as the required exposure is quite short.

It remains only to complete this brief outline of the best-known colour processes by referring to a method of using the diffraction grating for producing photographs in colours. This is the invention of Professor R. W. Wood of Wisconsin University. The production of a spectrum by means of a grating, and the character of the grating itself are well known to students of optics, so that these features need not be described here. The extent of the diffraction depends on the closeness of the rulings, and Professor Wood takes advantage of this fact for carrying out his process, using three gratings of 2000, 2400, and 2750 lines to the inch respectively. The finer the lines the more the spectrum is lengthened out and the farther it is from the central image. Fig. 68 illustrates the production of diffraction images by a grating.

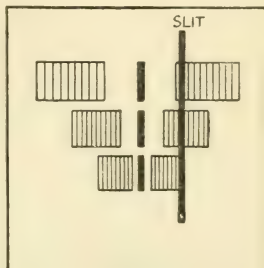


Fig. 69

With three gratings of the above degrees of fineness three spectra of the first order are obtained, occupying the positions shown on the diagram (fig. 69), and the red obtained with the coarsest ruling, the green with the medium ruling, and the violet with the finest ruling will be at the same distance from the

Professor Wood's
Example

Fig. 70

Red
TransparencyGreen
TransparencyBlue
Transparency

Fig. 71

central image. Hence if the images are thrown on an opaque screen, and a long slit is made in the screen as indicated in the diagram, we should see part of the length of the slit illuminated with red light, part with green, and part with violet.

Suppose now a set of three-colour negatives is made by the usual three-colour process through red, green, and blue-violet

screens in the manner already described, and that from these negatives positive transparencies are made, the result of these stages of the process will be seen from the following diagrams. Fig. 70 shows Professor Wood's example of a blue flower-pot on a white



Fig. 72

cloth. There are also a red flower and green leaves. Figs. 71 and 72 show the three-colour negatives and transparencies.

If now a piece of glass is taken and coated with a bichromated gelatine, covered with the grating of 2000 lines to the inch, then with the transparency made from the red negative, and exposed to light, the result if the plate were suitably developed would be



Fig. 73.—Diffraction Photograph

a reproduction of the ruling in varying degrees of relief. The red portions would be strongly represented, the half-tones by weaker rulings, and the opaque portions of the positive would be rendered by clear glass. The plate is not, however, developed after this first exposure; it is exposed again, this time under the "green" positive with the grating of 2400 lines to the inch. Finally, without developing this second image, the plate is exposed under the positive of the blue filter with the ruling of 2750 lines. The plate, after these

three exposures, is developed in warm water, with the result that the parts of the image corresponding to the various colours have each a different ruling. In an exaggerated degree this is shown by the shading in the diagram (fig. 73). Those parts of the original which were black will be reproduced as clear glass on the plate. When such a plate impressed with the three images is placed in the same position as the gratings originally occupied, and is looked at

through an aperture placed in the same plane as was occupied by the slit in the screen (fig. 69), the picture will show up brilliantly in colours. The parts with the coarsest ruling will appear red, those with the medium ruling green, and those with the finest ruling will be blue. The background with no ruling will, for the reason already mentioned, appear black, whilst any part which has in it all three rulings will be white, because the mixture of the three lights, red, green, and blue-violet, produces white.

Attempts have been made to utilize the phenomena of polarization to produce colour photography, but so far no satisfactory process has been evolved.

The processes described exemplify the fundamental principles of numerous other methods which have been from time to time put forward, and it is difficult to conceive any radically new lines on which research in colour photography can proceed.



The total amount transmitted

$$\begin{aligned} &= I_0(1 - \beta)^2 e^{-at} + I_0(1 - \beta^2)\beta^2 e^{-3at} + I_0(1 - \beta)^2\beta^4 e^{-5at} \\ &= I_0(1 - \beta)^2 e^{-at} (1 - \beta^2 e^{-2at})^{-1}. \end{aligned}$$

The value of the term $\beta^2 e^{-2at}$ will be, generally speaking, quite small. β is about $\frac{1}{25}$ for ordinary glass. Consequently the formula may be written

$$I_1 = I_0(1 - \beta)^2 e^{-at}, \text{ sufficiently nearly.}$$

Having measured the fraction $\frac{I_1}{I_0}$ for a plate of thickness t , we can make an allowance for reflection by assuming a value for β , in which case the formula reduces to

$$\log \frac{I_1}{I_0} = \log (1 - \beta)^2 - at.$$

If $\beta = \frac{1}{25}$ a practical formula may be given,

$$\log_{10} \frac{I_1}{I_0} = \log_{10} 0.92 + Kt.$$

In this case the coefficient K is known as the "extinction coefficient". (This term is sometimes used with another meaning. See Nutting's *Outlines of Applied Optics*, p. 12.)

By measuring the transmission of a plate of a second thickness t' , we may dispense with an assumed value for β . We shall get the value of

$$\begin{aligned} I' \text{ (say)} &= I_0(1 - \beta)^2 e^{-at'}; \\ \text{then } \frac{I_1}{I'} &= e^{a(t' - t)}, \text{ whence } a \text{ may be found.} \end{aligned}$$

We may thus calculate the transmission of any other thickness of material—allowing for reflection.

Variation of transmission with concentration. Beer's Law.—When applied to a solution of varying concentration c the exponential law of transmission becomes modified as follows:

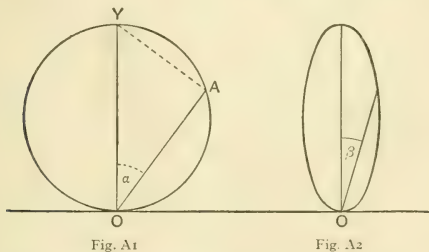
$$I_1 = I_0 e^{-act},$$

where a is taken as the absorption coefficient for unit concentration. The law only holds while the absorbing power of one molecule is uninfluenced by the action of its neighbours.

Diffuse reflection.—In the case of many materials, such as matt paper, the surface reflection will be diffuse and non-specular, or a combination of both may be found in surfaces like polished wood. The radiation from a perfectly diffusing surface follows *Lambert's law*, i.e. the intensity of

radiation from a small element of surface in any given direction is proportional to the cosine of the angle between that direction and the normal to the surface. In other words the surface would appear of the same brightness in all directions, the amount of light received by an eye looking at the surface being simply proportional to the apparent angular subtense of this latter. As this is the case it is possible to represent the nature of the reflection, as has been done by Trotter, by interesting diagrams ("polar curves") in which the intensity of reflection from a diffuse surface is plotted along the particular direction. A surface fulfilling Lambert's law gives a true circle for $OA = OY \cos a$ (fig. A1). The type of reflection given by frosted aluminium is shown in fig. A2.

Examples of the reflection of certain types of surface, represented in



A1, Polar curve for perfectly diffusing surface (normal illumination). A2, Polar curve for surface possessing greater proportional normal reflection, like aluminium paint, but lower efficiency.

a manner which will be obvious from an inspection of the diagram, are given in fig. A3. The curves are based on the results of H. Lebman (German Phys. Soc., 1908).

This question of the combination of diffuse and specular reflection is of very great importance in spectrophotometric measurements on opaque substances. It is almost obvious that the "colour" of a substance possessing such a property changes to an enormous extent with the angle of view, and therefore in any spectrophotometric measurements great care must be taken to ensure that the intensity of the specularly reflected light does not entirely overpower that which ordinarily gives the characteristic colour.

White matt surfaces may have total reflecting powers (*albedo*) of from 98 per cent downwards. For photometric work "magnesium white" is a very suitable but rather fragile surface, and is as white as anything known. A metal surface is prepared by holding it in the white "smoke" of burning magnesium. Zinc white, plaster of Paris, and white blotting-paper all make good non-selective white surfaces. Their reflecting powers

will vary only by one or two per cent throughout the spectrum in comparison with magnesium white.

Some interesting characteristics are shown by matt metallic surfaces such as that given by aluminium paint or ground glass backed by a silvered

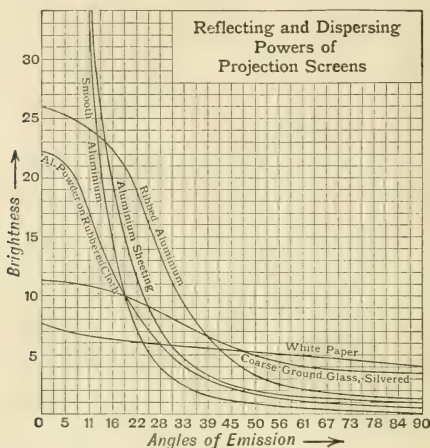


Fig. A3

surface. Projection screens of this type have effected economy of light by directing the maximum intensity of light where it is most needed.

EFFICIENCY OF PROJECTION SCREENS¹

Type.	Reflection Efficiency ² within 30°.	Total Reflecting Power.
Magnesium carbonate block ..	0.22	0.87
Aluminium paint	0.14	0.25
Becker compound	0.34	0.63
Ground mirror silvered on back ..	0.64	0.92

The integrating cylinder previously described in the text provides a means of standardizing the conditions under which the spectral reflection

¹ Table due to Nutting. Later results by Taylor (Bureau of Standards, Washington, *Scientific Papers*, No. 391) give higher values of total reflecting power of these surfaces, up to 98 per cent for magnesium carbonate.

² The proportion of the total light reflected within 30° from the normal.

coefficients of a substance are to be measured, the conception being that the surface is to be illuminated from all directions equally, as by an "infinite plane" of uniform brightness. The silvered walls, however, are by no means perfect reflectors, and Taylor believes that the results obtained are much too low. It seems now proved quite definitely that a freshly prepared magnesium carbonate surface follows Lambert's law very nearly, and reflects 98 per cent of the incident energy.

Considerations regarding the nature of the surface are of great importance in using colorimeters, and if the reflection is at all specular, it will be easy to obtain varying measures for the colour by altering the incidence of illumination on the surface, especially if intense *directed* light like sunlight is used for illumination.¹ It appears to be desirable in any case to avoid the specularly reflected light, and, as in the case of the integrating cylinder, to make the measurement under some prescribed standard conditions in which any serious differences in the amounts of specular reflection due to two surfaces will cause lessened differences in the colorimeter indications. It may be that colorimeters will in future be fitted with an illuminating fitting to receive sunlight or diffused daylight, and, in fact, it should not be difficult to design a modification of the integrating cylinder suitable for the present purpose. Until such a device is available the surface under examination should be supported at right angles to the tube or line of observation, and illuminated so that the light is incident at an angle of about 45° . This can easily be arranged with a mirror. It will of course be perfectly obvious that the complete colour properties of a surface cannot be specified by a single measurement with one angle of incidence of the light. The whole subject is one calling for the most careful consideration.

(2) Units of Light

The practical unit of light is the "lumen". This is the amount of light radiated into unit solid angle by a uniformly radiating source of 1 candle power.

(Unit solid angle would be represented by the solid angular subtense of an area of 1 sq. ft. on the surface of a sphere of 1 ft. radius.)

In accordance with the cosine law of radiation for diffusing surfaces it is easily proved that if a surface radiates normally with a power corresponding to B candles per unit area, the total amount of light radiated into space is πB lumens (on the one side of the surface).

The unit of brightness called the *lambert* corresponds to the brightness of a perfectly diffusing surface radiating or reflecting 1 lumen per square centimetre. The milli-lambert is one-thousandth part of this. Hence

¹ Compare fig. 48, which shows a most undesirable method of illumination.

the normal radiation corresponds to $\frac{1}{\pi}$ candles per square centimetre when the brightness is 1 lambert.

The unit of illumination known as the *foot-candle* is the illumination at a point 1 ft. distant from a point source of unit power (1 candle power).

Hence the quantity of light received by 1 sq. ft. of a surface on which the illumination is 1 foot-candle is equal to 1 lumen.

$$\begin{aligned}\text{Now 1 lumen per square foot} &= \frac{1}{(12 \times 2.54)^2} \text{ lumens per square centimetre} \\ &= .001076 \text{ lumens per square centimetre.}\end{aligned}$$

Let the surface have a reflection coefficient or *albedo* m , and let it also be a perfectly diffusing surface, then

$$\text{Light radiated per square centimetre} = (.001076)m \text{ lumens.}$$

$$\begin{aligned}\text{Hence the brightness of a surface when} \\ \text{the illumination is 1 ft.-candle} \quad \dots \quad &= m(.001076) \text{ lamberts} \\ &= m(1.076) \text{ milli-lamberts.}\end{aligned}$$

Small commercial photometers (such as the *Holophane Lumeter*) are available, by means of which the brightness of an illuminated field may be measured. The *lumeter* reads in foot-candles, that is to say the brightness which a perfectly reflecting and diffusing surface would have if illuminated by so many foot-candles.

With this instrument one can actually look into the field of another instrument and thus get the brightness in apparent foot-candles. Multiplying by 1.076 gives the value in milli-lamberts. If it is not convenient actually to look into the field of the photometer (or &c.) with the lumeter, a comparison field could be arranged outside and adjusted to have about the same brightness as that in the instrument. The comparison field might then be viewed with the lumeter. In this way we may judge as to whether the most suitable intensity of light is being used in the photometer.

(3) Dichroism

An algebraical statement may make the matter more clear.

Let I_r and I_b be the physical intensities of the light in two regions (red and blue, say) where a substance has transmission bands. Let L_r and L_b be the relative luminosity coefficients for these spectral regions. Then the corresponding actual visual brightnesses will be

$$I_r L_r \text{ and } I_b L_b.$$

It is easy to imagine L_r much less than L_b ; we have to remember also

that the L 's are approximately constant. We now suppose that after passing through unit thickness of solution all light is absorbed except in these regions for which the corresponding transmission coefficients are a_r and a_b , say. Then the relative visual brightnesses of the components of the transmitted light are

$$I_r L_r a_r \text{ and } I_b L_b a_b.$$

Let a_r be 0.9, say, and $a_b = 0.5$. Then, even though $I_r L_r (0.9)$ be still less than $I_b L_b (0.5)$, it will easily be realized that owing to the exponential law of absorption the relative intensities after passing through five units length,

$$I_r L_r (0.9)^5 \text{ and } I_b L_b (0.5)^5, \text{ or } I_r L_r (0.59) \text{ and } I_b L_b (0.031),$$

may well be reversed, the brightness of the blue being probably negligible in comparison with that of the red.

(4) TABLE SHOWING WAVE-LENGTHS OF SPECTRUM LINES,¹
OFTEN USEFUL IN COLOUR-WORK

Substance.	How Emitting Light.	Wave-length in mm. = μ . 1000	Colour.
Sodium ..	In Bunsen flame	<i>.5890</i>	Yellow-orange
		<i>.5896</i>	Red "
Potassium ..	In Bunsen flame	<i>.767</i>	"
		<i>.770</i>	"
		<i>.404</i>	Violet
Lithium ..	In Bunsen flame	<i>.405</i>	"
Strontium ..	In Bunsen flame	<i>.671</i>	Red
		<i>.461</i>	Blue
Hydrogen ..	Vacuum tube	<i>.656</i>	Red
		<i>.486</i>	Blue-green
		<i>.434</i>	Violet
		<i>.6230</i>	Red
		<i>.579</i>	Yellow
Mercury ..	(Mercury lamp)	<i>.577</i>	"
		<i>.546</i>	Green
		<i>.408</i>	Violet
		<i>.405</i>	"

¹ The more intense lines are indicated by italics.

(5) TABLE SHOWING TYPICAL REGISTRATION OF COLOUR IN TERMS OF HUE, SATURATION, AND BRIGHTNESS (AFTER ABNEY)

Colour.	Dominant Hue, μ .	Percentage of Saturation.	Luminosity, White = 100.
Vermilion pigment ..	·610	97·5	14·8
Emerald green pigment ..	·522	41	22·7
French blue pigment ..	·472	39	4·4
Brown paper ..	·594	50	25
Brown paper (greyer) ..	·567	33	19·5
Orange	·591	96	62·5
Chrome yellow	·583	74	77·7
Blue-green	·500	57·5	14·8
Eosin dye (<i>Sporting Times</i>)	·640	28	44·7
Cobalt	·482	44·5	14·5

(6) TABLE SHOWING TEMPERATURES OF SOURCES OF LIGHT AND WAVE-LENGTHS FOR MAXIMUM ENERGY IN THE SPECTRUM

	λ_m	Estimations of Temperature.	
		Maximum.	Minimum.
Candle	1·5 μ	1700° C.	1500° C.
Argand lamp	1·55 μ	1600° C.	1400° C.
Acetylene flame	1·05 μ	2500° C.	1800° C.
Incandescent mantle	1·2 μ and 9·5 μ	1800° C.	1600° C.
Electric lamp (carbon filament) ..	1·4 μ	1850° C.	1800° C.
Nernst glower	1·2 μ	2200° C.	1500° C.
Electric arc (carbon poles) ..	·7 μ	4000° C.	3500° C.
Sun	·59 μ	6000° C.	5000° C.
Blue sky	·45 μ	—	—

(7) TABLE SHOWING SPECTRAL LUMINOSITIES AND PERCENTAGE COMPOSITION OF SPECTRAL LIGHTS IN TERMS OF PRIMARY SENSATION LUMINOSITIES.

(After Abney, *Researches in Colour Vision*, 1913)

Abney's Scale Number.	Wave Length in μ .	Luminosity of Spectrum (Arc Light and Prismatic Dispersion).	Red, Green, and Violet Sensations.			Red, Green, and Blue Sensations.			Percentage Composition of Sensations, White being Deducted.		
			Percentage Composition.			Percentage Composition.			R.S.	G.S.	B.S.
			R.S.	G.S.	V.S.	R.S.	G.S.	B.S.			
64	7217	0.5	100	—	—	100	—	—	100	—	—
62	6957	2	100	—	—	100	—	—	100	—	—
60	6728	7	100	—	—	100	—	—	100	—	—
58	6521	21	99	1	—	99	1	—	99	1	—
56	6330	50	95.5	4.5	—	95.5	4.5	—	95.5	4.5	—
54	6152	80	90.5	9.5	—	90.5	9.5	—	90.5	9.5	—
52	5996	96	84.2	15.8	—	84.2	15.8	—	84.2	15.8	—
50	5850	100	75	25	—	75	25	—	75	25	—
48	5720	97	67.0	33	.07	67.05	33	.020	67.1	32.9	—
46	5596	87	62.0	37.9	.11	62.03	37.9	.031	59.9	40.1	—
44	5481	75	57.7	42.1	.15	57.21	41.9	.042	51.1	48.9	—
42	5373	62.5	54.9	44.9	.24	55.04	44.9	.067	40.1	59.9	—
40	5270	50	51	48.6	.42	51.30	48.6	.117	27.4	72.6	—
38	5172	36	48	51.3	.82	48.52	51.3	.230	10.9	89.1	—
36	5085	24	45	53.5	1.500	46.08	53.5	.420	—	99.6	.386
34	5002	14.2	41.5	55.34	3.11	43.79	55.34	.870	—	98.31	1.69
32	4924	8.5	37.8	56.13	6.07	42.17	56.13	1.700	—	96.24	3.76
30	4848	5.7	34.1	54.6	11.28	42.24	54.6	3.160	—	93.18	6.82
28	4776	4	30.7	50.54	18.75	44.36	50.54	5.200	—	87.37	12.63
26	4707	2.8	27.7	41.3	31	50.02	41.30	8.680	—	68.8	31.6
24	4639	1.95	24	28	48	58.56	28	13.44	—	10.5	89.5
22	4578	1.4	20.2	16.3	63	65.56	16.3	17.64	15	—	85
20	4517	1.1	16	8	76	70.72	8	21.28	60.7	—	30.3
18	4459	.86	11.4	4.6	84	71.88	4.6	23.52	71.8	—	28.2
16	4404	.70	6	2	92	72	2	25.76	73.1	—	26.9
14	4349	.56	1.5	0.5	98	72	0.5	27.44	72	—	28
12	4296	.45	—	—	100	72	—	28	72	—	28
10	4245	.35	—	—	100	72	—	28	72	—	28
8	4198	.26	—	—	100	72	—	28	72	—	28
6	4151	.18	—	—	100	72	—	28	72	—	28
4	4106	.14	—	—	100	72	—	28	72	—	28
2	4062	.10	—	—	100	72	—	28	72	—	28
0	4010	.06	—	—	100	72	—	28	72	—	28

Note.—The latest results embodied in above table slightly modify the "blue" curve in fig. 58, p. 131, and remove the "hump" at 5400.

(8) NOTE ON FIG. 30

Fig. 30 includes three wedge absorption spectra of Wratten filters (reproduced by the kind permission of Messrs. Kodak, Ltd.) which are suitable for use in "haze-cutting". This may be explained as follows. When a mist or haze is present distant objects are seen, as it were, through a veil of scattered light, and, as was pointed out on p. 42, the liability of light to the scattering effect is greater the shorter its wave-length. The use (before the eye or camera) of a colour filter which absorbs the shorter wave-lengths tends thus to absorb the light scattered from the mist, and also gives greater prominence to the longer wave-lengths which are less affected. A considerable increase of visibility may be obtained in this way.

Many other types of special colour filters have been developed for special purposes. Suppose, for example, that it is required to increase the contrast between an orange-yellow and a yellow-green. The use of a filter having a strong absorption in the yellow would perhaps transform the contrast into one between blue-green and red. Devices of this kind are extensively used for nautical, naval, and military purposes.

INDEX

- Abney's researches, 10, 60, 66, 83, 88, 94, 96, 129-36, 150, 180. See also *Colour-patch apparatus*.
- Absorption of light, 23-5, 68. See also *Selective absorption and reflection*.
- Acetylene flame, 43, 180.
- Achromatopia. See *Monochromatic vision*.
- Action of light on water colours, 66.
- Additive mixing of coloured lights. See under *Colour analysis and synthesis*.
- After images, 118.
- Air, action of, on pigments 65, 66.
- Alcohol amblyopia, 141.
- Alhazen (Arab), 1.
- Alizarin dye, 70, 74.
- Alizarin green, 75.
- Alizarin red pigment, 73.
- Allen, Frank, 117, 125, 134-8.
- Aluminium, 72.
- Aluminium paint, 72.
- American Medical Association, 147.
- Aniline dyes, 25, 47, 70.
- Annulus, 84, 93.
- Anomalous matches, 150.
- Anomalous trichomats, 140, 141.
- Antimony red pigment, 72.
- Antwerp blue pigment, 66, 67, 73-6.
- Argand lamp, 180.
- Arons colorimeter, 38, 113, 114.
- Artificial daylight. See under *Colour in regard to illumination*.
- Artificial light. See under *Colour in regard to illumination*.
- Asphaltum pigment, 75.
- Atlas of Absorption Spectra, 71.
- Aubert's experiments with colour discs, 88.
- Aureolin pigment, 74, 76.
- Aurora yellow pigment. See *Cadmium yellow pigment*.
- Autochrome (Lumière) process, 21, 167, 168.
- Auto-suggestion. See *Self-suggestion*.
- Barr, Mark, 47.
- Baryta white pigment, 73.
- Bawtree's colorimeter, 32, 38, 108-10.
- Bead test, 145.
- Beer's law, 114.
- Belli Arti, Accademia di (Florence), 55.
- Benham's disc, 1.
- Bistre pigment, 73.
- Bitumen pigment, 73.
- Black pigments, 72, 74.
- Blanchard on reactions of the eye to light, 86.
- Block printing, 151, 153.
- Blue-sky light, 42-51, 180.
- Bock-Benedict colorimeter, 115.
- Bolometer, 41.
- Bottle glass manufacture, 68.
- Bradford, E. J. G., 54.
- Brady. See *Ives and Brady's colouring matching glass*.
- Brightness, 12, 13, 32, 35, 78, 81-92, 116, 129-32, 140, 180.
- Brodhun's investigations in contrast sensibility, 89, 90. See also *Lummer-Brodhun*.
- Brown madder pigment, 75, 76.
- Brown pink pigment, 75.
- Burnt sienna pigment, 66, 72, 74, 76.
- Burnt umber pigment, 66, 72, 74, 76.
- Cadmium yellow pigment, 65-7, 72, 74, 76.
- Caledonian brown pigment, 76.
- Cameras for colour photography, 163-5.
- Camouflage. See under *Colour in human experience, Protective colouring, and camouflage*.
- Campbell Hurley's colorimeter, 115.
- Candle light, 180.
- Cappagh brown pigment, 74.
- Carbonates, classification, 73.
- Card test, 147.
- Carmine pigment, 66, 73, 75.
- Cartesian co-ordinates, 33.
- Central scotoma, 141, 145.
- Chance Brothers, Birmingham, 47.
- Charcoal, radiation by, 40.
- Charcoal black pigment, 72.
- Chemical classification of pigments. See under *Colouring materials*.
- Cheshire, Professor, 17.
- Chevreul on aesthetic values, 55.
- Chiaroscuro method, 152.
- Child welfare, 57.
- Chinese white pigment, 72, 74.
- Chinese wood-block printing, 151.
- Chromates, classification, 73.
- Chrome greens, 75.
- Chrome yellow pigment, 73, 75, 76.
- Chromium oxide pigment, 67, 68.
- Chromo-lithography, 153-8.
- Chromoscopes. See under *Colour analysis and synthesis*.
- Chrysanthémistes (France), Société des, 30.
- Cinematograph. See *Kinematograph*.
- Cinnabar greens, 75.
- Clerk Maxwell's colour box, 126-9.
- Cloud and fog, 43.
- Cobalt, 68.
- Cobalt pigments, 67, 68, 72-6.
- Cæruleum pigment, 72, 74.
- Cohn, J., 54.
- Collimator lens, 14, 17, 101, 126.
- Collotype, 153.
- Colorimeters, 37, 38, 177. See also under *Instruments for colour measurement*.
- Colorimetric Analysis, 115.
- Colour, definition of, 11, 12.
- Colour, nature of. See *Light and colour, nature of*.
- Colour analysis and synthesis, 14-22.
- Additive mixing of coloured lights, 16-9.
- Chromoscopes, 22.
- Colour discs, 20, 21.
- Complementary hues, 20, 21.
- "Overlapping", 21, 22.
- Selection of wave-lengths, 16.
- Spectroscopic, 14-6.
- Trichromatic theory, 19, 20.
- Colour and health. See under *Colour in human experience*.
- Colour atlas. See *Colour charts*.

- Colour blindness, 135-50.
 Anomalous matches, 150.
 Colour-blind standpoint, 141-2.
 Measurements of sensation deficiency, 148, 149.
 Tests for colour blindness, 144-50.
 Tests of colour vision, 143, 144.
 Trichromatic theory, 142, 143.
 Colour charts, 29-36.
 Colour contrasts, 54, 55.
 Colour discs. See under *Colour analysis and synthesis*.
 Coloured glass, 68, 69.
 Colour fatigue, 124, 125. See also under *Colour in human experience*, also *Colour vision*.
 Colour fields. See under *Eye and its reactions to light*; *Photometry*.
 Colour filters, 44-52, 72, 98, 107, 110, 155, 163, 182. See also under *Colours of material objects*.
 Colour harmony. See under *Colour in human experience*.
 Colouring materials, 63-76.
 Chemical classification of pigments and tables of stability, 72-5.
 Dyes, 70-2.
 Glass, pottery, and enamels, 68-70.
 Pigments and painting, 64-7.
 Colour in human experience, 53-62.
 Colour and health, 56, 57.
 Colour fatigue, 57-9.
 Colour harmony, 54-6.
 Colour music, 56.
 Colour preferences, 54.
 Intensity, effects of, 61, 62.
 Protective colouring, and camouflage, 56.
 Use and study of colour, development in, 53.
 Visual fatigue, 57-9.
 Colour in nature. See under *Light and colour, nature of*.
 Colour in regard to illumination, 39-52.
 Artificial daylight, 46-52.
 Artificial light, characteristics of, 43, 44.
 Colour of objects, effects of variation in light on, 44-46.
 Daylight and its variations, 42, 43.
 Natural and artificial light, 39-41.
 Radiating bodies, 40, 41.
 Spectral distribution of the energy of light sources, 41.
 Colour measurement. See *Colour nomenclature and measurement*. See also *Instruments for colour measurement*.
 Colour music. See under *Colour in human experience*.
 Colour nomenclature and measurement, 28-31, 37, 38.
 Colour notation, 110, 111. See also under *Colours of material objects*.
 Colour-patch apparatus, 19, 25, 37, 45, 60, 124, 136. See also under *Instruments for colour measurement*.
 Colour-patch test, 147.
 Colour photography. See *Photography in colours*.
 Colour preferences. See under *Colour in human experience*.
 Colour printing, 151-9.
 Colour pyramids. See under *Colours of material objects*.
 Colours of material objects, 23-38.
 Colour charts, 29-36.
 Colour filters, 24-7, 32.
 Colour nomenclature and measurement, 28-31, 37.
 Colour notation, 28, 29.
 Colour pyramids, 32, 33.
 Dichroism, 25, 26.
 Maxwell's colour triangle, 31, 32.
 Nobili's colour scale, 36, 37.
 Spectral reflection of "coloured materials", 26, 27.
 Subtractive colour mixing and mixing of pigments, 27-9, 38.
 Colour tree, 33-6.
 Colour triangle. See *Maxwell's colour triangle*.
 Colour vision, 117-38.
 Colour fatigue, 134, 135.
 Determination of hue, saturation and brilliance of a surface, 132, 133.
 Edridge-Green theory, 123-6.
 Hering's theory, 120-2.
 Hue sensations in spectrum, measurement of, 126-8.
 Ladd Franklin theory, 122, 123.
 Primary hue sensations, 128-32.
 Spectrum colours, change in hue of, 133, 134.
 Trichromatic theory, 119, 120.
 Visual fatigue, 134, 135.
 Complementary hues, 34, 55, 121, 128. See also under *Colour analysis and synthesis*.
 Contrast sensibility, 89, 90.
 Crimson lake pigment, 66, 73-6.
 Crookes' experiments with coloured glass manufacture, 68, 69.
 Cylindrical co-ordinates, 33, 34.
 Dalton's colour blindness, 140.
 Daylight, 9, 39, 51. See also *Colour in regard to illumination*.
 Definitions, list of, 11, 12.
 Deuteranopes, 140, 141.
 Dichroism, 72, 178, 179. See also under *Colours of material objects*.
 Dichromat, 140, 141.
 Dieterici's luminosity curves, 130, 131.
 Diffraction discs, 70.
 Diffraction gratings, 16, 169-71. See also under *Instruments for colour measurement*.
 Diffuse reflection, 174, 175.
 Direct vision spectroscopy, 15-7.
 Dispersion, effect of, on distribution of energy in the spectrum. See under *Eye and its reactions to light*.
 Distempers, 64.
 Domestic lighting, 46, 51.
 Dress, colour in, 54, 56.
 Duboscq colorimeter, 38, 114.
 Dufay screen-plate process, 167.
 Dufton and Gardner's lamp, 46.
 Dutch engraving, 152.
 Dyeing, 25, 26, 45, 51. See also under *Colouring materials*.
 Earth pigments, 53, 72-6.
 Eastman, Ltd., dyers, 45.
 Edridge-Green on colour blindness, 142, 144-7.
 Edridge-Green theory. See under *Colour vision*.
 Egyptian blue, 53.
 Egyptian painting, 53.
 Eimer & Amend, New York, 114.
 Electric lamps, 43, 44, 156, 180.
 Elements, classification of, 72.
 Emerald green pigment, 67, 73, 75, 132, 180.
 Emerald green substitute, 73.
 Enamels. See under *Colouring materials*; *glass, pottery, and enamels*.
 English vermilion deep, 35.
 Engraving, 152.
 Eosine dye, 180.
 Eye, 16, 21, 45. See also under *Light and colour, nature of*; also *Eye and its reactions to light*.
 Eye and its reactions to light; photometry, 77-95.
 Colour fields, 70-81.
 Construction of eye, 77-9.
 Contrast sensibility, 89-91.
 Effect of dispersion on the distribution of energy in spectrum, 92.
 Hue limen, 87, 88.
 Luminosity variations in spectrum, 93-5.
 Non-achromatism, 81.
 Photometric wedges, 83.
 Polarizing prisms, 84, 85.
 Purkinje effect, 91.

- Eye and its reactions to light:
 Reaction of eye to light, 85-7.
 Threshold of vision, 95.
 Tone limen, 88, 89.
 "True" sensation measurement, 91, 92.
 Visual measurement and comparison of
 brightness, 81-2.
 Eye protection, 68, 69.
- Fechner on colour sensation, 1.
 Ferree on colour fields, 80.
 Firelight, 9, 10.
 Flake white. See *White lead*.
 "Flicker" methods, 134, 135. See also under
Eye and its reactions to light.
 Florence, 37.
 Fluorescence. See under *Light and colour, nature of*.
 Fog, 43.
 Four-colour printing, 158.
 Fovea, 79, 95, 139, 141.
 Freeman's white pigment, 73.
 French blue pigment, 180.
 Fresco, 53.
 Fresnel on wave theory of light, 2.
- Gamboge pigment, 66, 67, 73, 76.
 Garnett on physical optics, 70.
 Gaze, Dr., 47.
 Geissler's experiments, 88, 89.
 Glan-Thomson prism, 84, 99, 101.
 Glass, colouring of. See *Coloured glass*.
 Glazebrook spectrophotometer, 38.
 Gold, 68, 72.
 Græbe and Liebermann's dye, 70.
 Graphite, 72.
 Greek painting, 53.
 Green chromium oxide, 72.
 Green glass, 68, 69.
 Grey pigments, 74.
 Gum-bichromate photographic printing, 64.
- Half-tone block process, 153-5.
 Half-watt lamp, 43, 47, 49.
 Harvard psychological laboratory, 57.
 Health and colour, 56, 57.
 Health and colour blindness, 147.
 "Hektograph" pad, 165.
 Helmholtz on hue sensation, 20, 121.
 Hering's theory, 32, 33. See also under *Colour vision*.
 Hilger, A., Ltd., 100, 105, 147.
 Holman Hunt, William, 67.
 Holmgren wool test, 145-7.
 Holophane lumeter, 178.
 Hooker's green pigment, 75.
 Houston on colour mixing, 32, 124.
 Howells, W. A., 56.
 Hue, complementary. See *Complementary hues*.
 Hue and wave-length. See under *Light and colour, nature of*.
 Hue limen. See under *Eye and its reactions to light*.
 Hue scale, 88.
 Hue sensations in spectrum, measurement of.
 See under *Colour vision*.
 Huygens' theory of space, 1.
 Hyde on rotating sectors, 83.
 Hydroxides, classification of, 72.
- Illuminating Engineer*, 49.
 Illustrations of books, 151, 152.
 Incandescent mantle, 15, 43, 44, 180.
 Indian ink pigment, 72.
 Indian lake pigment, 73.
 Indian red pigment, 66, 74.
 Indian yellow pigment, 73, 75.
 Indigo pigment, 65, 67, 73.
 Inks for colour printing, 151, 157-9.
- Instruments for colour measurement, 96-116.
 Colorimeters, 104-15.
 Colour-patch apparatus, 96-8.
 Diffraction gratings, 98, 99.
 Nephelometer, 115.
 Photometric comparison cube, 103, 104.
 Spectrophotometers, 99-103.
 Tintometer, 110-2.
 Integrating cylinder, 102, 103, 177.
 Intensity, effects of. See under *Colour in human experience*.
 Interference colours, 36.
 "Inverse square" law, 82.
 Iron, 68, 72.
 Italian pink pigment, 75.
 Ives and Brady's colour matching glass, 47.
 Ives colorimeter, 38, 107, 110.
 Ives kromscop, 166, 167.
 Ives on artificial daylight, 47.
 Ivory black pigment, 72, 76.
- Japanese wood-block printing, 151.
 Joly's screen-plate process, 167, 168.
 Jones colorimeter, 113.
 Jones on hue and tone limen, 87, 88.
Journal of the Royal Society of Arts, 66, 67.
- Kemp-Prossor on therapeutics, 57.
 Kinematograph, 135.
 King's yellow pigment, 72.
 Klein, Major, 47.
 Kober colorimeter, 115.
 Kodak Company, 20, 72, 124, 182.
 König-Martens instruments, 26, 38, 100-2.
 König's investigations in contrast sensations, 89, 90.
 König's investigations in spectral luminosities, 94, 95, 130.
 Kries, von, on reactions of eye to light, 79, 140.
 Kromscop, 166, 167.
- Ladd Franklin theory. See under *Colour vision*.
 Lambert's law, 174-8.
 Lamp black pigment, 72.
 Lantern test, 144, 145.
 Laurance, Lionel, 77.
 Le Blon, James Christopher, 152.
 Lemon yellow, 74, 76.
 Lens, 2-7, 14, 17, 40, 77, 96, 97.
 Light, action of, on pigments, 66.
 Light, reactions of eye to. See *Eye and its reactions to light*.
 Light, sources of (table), 180.
 Light and colour, nature of, 1-13.
 Colour in nature, 9, 10.
 Definitions, 11, 12.
 Eye, 5, 6.
 Fluorescence, 8.
 Hue and wave-length, 10, 11.
 Newton's experiment, 6, 7.
 Ray paths in prisms and lenses, 3-5.
 Selective reflection and absorption, 7, 8.
- Light filters. See *Colour filters*.
 Light red pigment, 72, 74.
 Limited range colorimeters, 38, 114.
 Line spectrum, 7, 14, 81.
 Lippman, Professor, 160, 161.
 Listing on hue and wave-length, 10.
 Lithography, invention of, 152, 153.
 Lovibond on colour nomenclature, 28.
 Lowry on instruments for colour measurement, 111.
 Luckiesh on artificial daylight, 47, 51.
 Luckiesh on colour preferences, 54.
 Luminosity measurement, equations of, 129, 130.
 Luminosity test, 149.
 Luminosity variations in spectrum. See under
Eye and its reactions to light.
 Lummer and Kurlbaum's experiments, 41.
 Lummer-Brodhun adjustable sectors, 98.
 Lummer-Brodhun comparison prism, 103, 104, 113.

Lummer-Brodhun "head", 39.
Lustre ware, 70.

M'Hatton on colour measurement, 111, 112.

Macula lutea, 78, 141.

Madder carmine, 75.

Magenta hue, 8, 18, 26, 75.

Malachite green pigment, 73, 75.

Manganese, 68, 72.

Mars brown, red, orange, 74.

Mauve hue, 70, 75.

Maxwell's colour triangle. See under *Colours of material objects*.

Mees, Kenneth, 46, 71.

Mercury lamp, 7, 15.

Metal engraving, 152.

Mezzotint, 152, 153.

Mineral violet pigment. See *Permanent violet pigment*.

Monochromatic vision, 57, 58, 96, 104, 107, 141.

Monochromator, 16.

Munsell, A. H., 30, 31, 33-6.

Nagel's anomaloscope, 150.

Nagel's card test, 147.

Naples yellow pigment, 73.

Nature of light and colour. See *Light and colour, nature of*.

Nela research laboratory, 41, 48.

Nephelometer, 115.

Nernst glower, 180.

Neurasthenia, 57.

Newspaper printing, 154.

Newton, Sir Isaac, 3, 6, 7, 36.

Nichols' experiments, 43.

Nickel, 68.

Nicol prism, 84, 85, 101.

Nisbet on oil painting, 76.

Nobili's colour scale, 36, 37.

Nodal points, 78.

Non-achromatism. See under *Eye and its reactions to light*.

North light, 39, 44, 51, 111.

Nutting's colorimeter, 104-7.

Nutting's investigations in colour vision, 38, 87-90, 94, 99, 104.

Nutting's spectrophotometer, 99, 100.

Ocentric Optical Company, 17.

Ochres, 65, 72.

Oil painting, 53, 65, 74-6. See also *Pigments*.

Oil Painting (Nisbet), 76.

Omnicolor plate process, 167.

Organic compounds, classification of, 73.

"Overlapping". See under *Colour analysis and synthesis*.

Oxides, classification of, 65, 72.

Ozotype process, 165, 166.

Paint enamels, 65.

Painting, 27, 53, 55, 58-67, 72-6. See also *Oil painting*, *Pigments*, and *Water-colour painting*.

Painting, ancient forms, 53.

Paper for printing, 157, 159.

Paterson on colour mixing, 25.

Perimeter, 80.

Perkins, Sir W. N., 70.

Permanent violet pigment, 73.

Photography, 8, 9, 21, 43, 64, 71, 72.

Photography in colours, 160-71.

Photography in regard to colour printing, 153-6.

Photogravure, 158.

Photometer, 32, 39, 100-2, 178.

Photometric comparison cube. See under *Instruments for colour measurement*.

Photometric wedges. See under *Eye and its reactions to light*.

Photometry. See under *Eye and its reactions to light*.

Physical Optics (R. W. Wood), 70.

Picture theatre lighting, 87.

Pigmentation of macula, 141.

Pigments, 20, 27, 35, 53, 62. See also under *Colouring materials*.

Pigments, chemical classification of, 72-6.

Pigments in colour printing, 151, 157.

Pigments, tables of stability, 74-6.

Pigmentum epithelium, 78.

Pinachrome process, 165.

Polarizing prisms, 113, 114. See also under *Eye and its reactions to light*.

Porter on persistence of vision, 135.

Posters, 154.

Pressey, Dr., 57.

Primary hue sensations. See under *Colour vision*.

Printing. See *Colour printing*; see also *Three-colour printing*.

Prism, 3, 6, 15-8, 27, 40, 84, 96.

Projection screens, 176.

Protanopes, 40, 141.

Protective colouring. See under *Colour in human experience*.

Prussian blue pigment, 66, 73, 75.

Purkinje effect, 61, 118, 140. See also under *Eye and its reactions to light*.

Radiating bodies. See under *Colour in regard to illumination*.

Rand on colour fields, 80.

Raw sienna pigment, 74, 76.

Raw umber pigment, 72, 74.

Rayleigh, John William Strutt, third Baron, 11, 42, 141.

Ray paths, 15, 18. See also under *Light and colour, nature of*.

Reeves, Messrs., 76, 124.

Reflection of light, 23, 26, 38, 175.

Reflectors of light, 46-52.

Retina, 5, 16-21, 55, 58, 77-80, 85-7, 120, 125, 139, 141.

Rhodamine dye, 8, 25.

Richardson, Messrs., 30.

Ridgway's coloured cards, 30.

Rimington's colour organ, 56.

Rivers on binocular colour mixture, 22.

Rods and cones, 77, 123.

Rose madder pigment, 73, 75.

Rotating sector, 82, 83, 107.

Royal Society, 146.

Russell and Abney on stability of pigments, 66.

Ruxton, Messrs., 30.

Sap green, 73, 75.

Saturation, 12, 13, 19, 23, 30, 33-6, 38, 64, 109, 132, 180.

Schweinfurt green, 73.

Scientific Method (Westaway), 117.

Scotomata, 141.

Screen-plate processes, 166-8.

Selective reflection and absorption. See under *Light and colour, nature of*.

Self-suggestion, 62.

Sepia pigment, 73, 75.

Shadows, 39, 62.

Shell shock, 57.

Sherrington, George, 47, 51.

Shop lighting, 51.

Siedentopf's ultra-microscopic method, 70.

Silenium, 68.

Silicates, classification of, 73.

Spectral distribution of energy of light sources.

See under *Colour in regard to illumination*.

Spectral luminosity, 181.

Spectral reflection of coloured materials. See under *Colours of material objects*.

Spectral visibility, 93.

Spectrograph, 71.

Spectrophotometer, 15, 25, 26, 37, 85, 132, 133.

See also under *Instruments for colour measurement*.

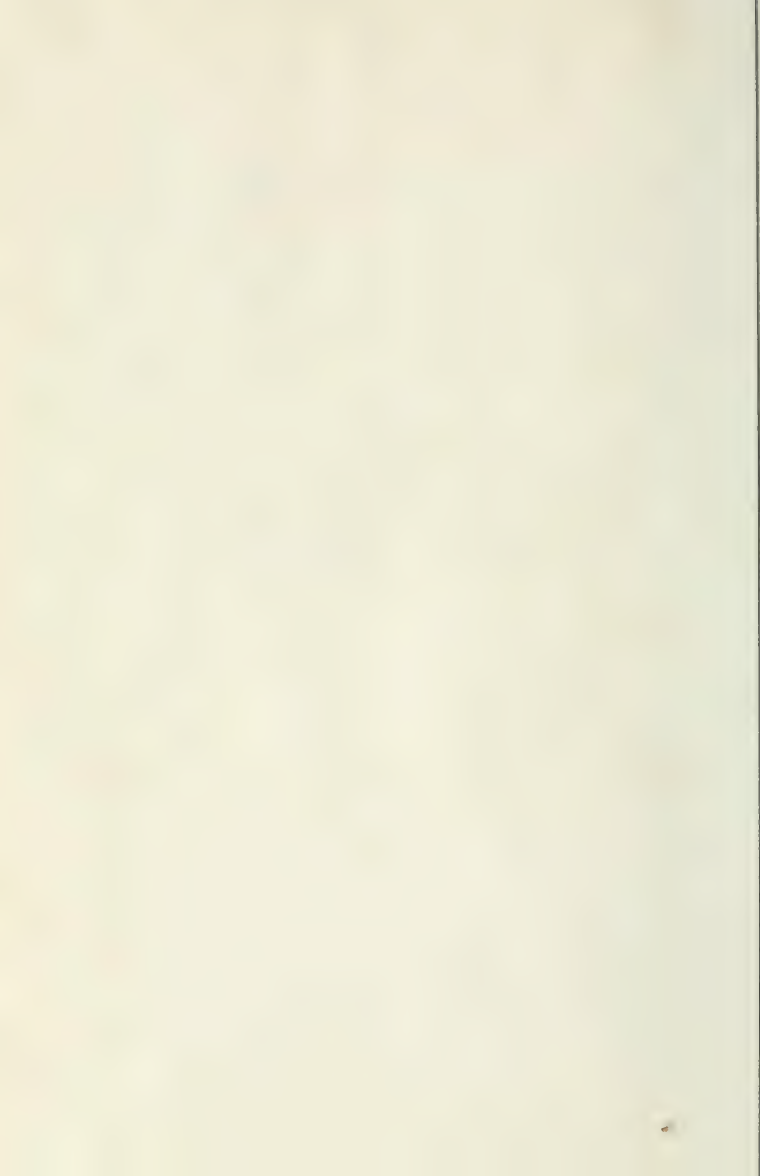
Sporting Times, 180.

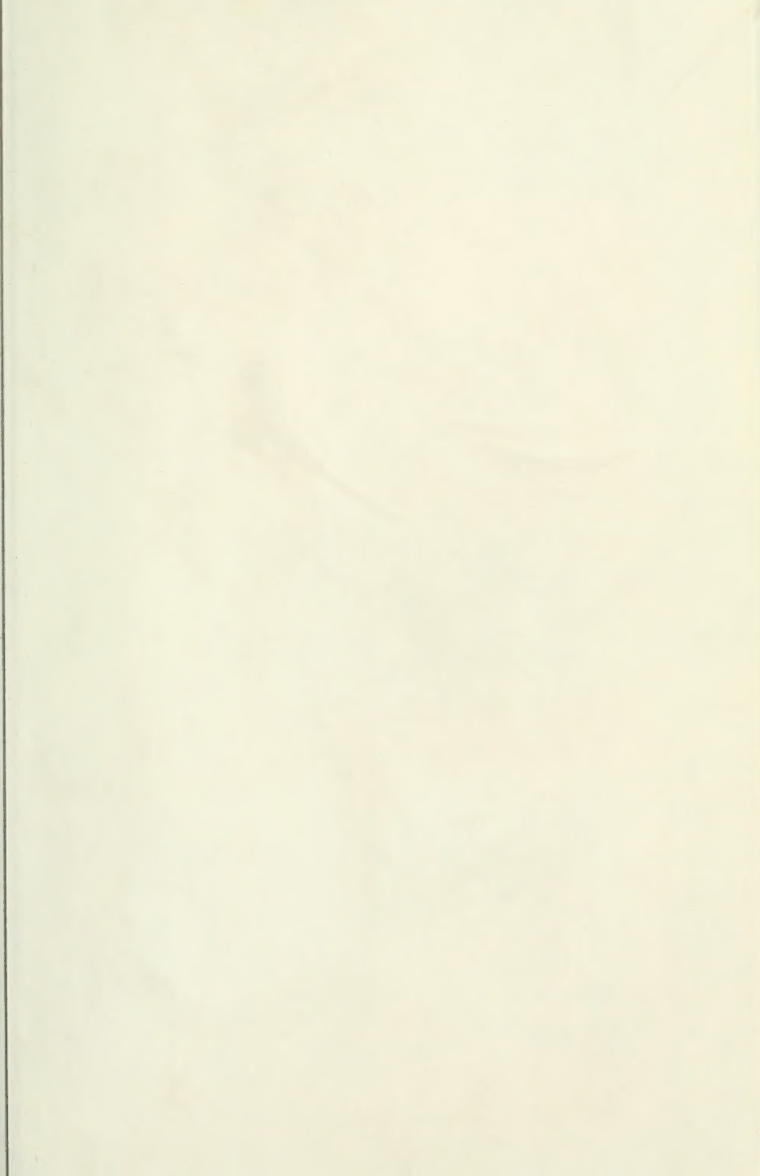
Stained glass. See *Coloured glass*.

- Steindler on hues in spectrum, 124.
 Stoving enamels, 65.
 Subtractive primaries, 27, 74, 76.
 Suggestive colours, 57.
 Sulphides, classification of, 65, 72.
 Sunlight, 42-51, 180.
 Surface of materials, 23, 174-7.
 Swan's comparison cube, 103.
- Terre verte* pigment, 67, 73, 74, 76.
 Tests for colour blindness and colour vision.
 See under *Colour blindness*.
 Thames plate process, 167.
 Theatrical stage lighting, 51, 52.
 Therapeutics, 57.
 Thomas, W. Cave, 55.
 Three-colour mixture colorimeters, 107, 108.
 Three-colour printing, 28, 152, 153.
 Three-colour theory. See *Trichromatic theory*.
 Threshold of vision. See under *Eye and its reactions to light*.
 Tintometer, 29, 38, 110-2.
 Titchener's colour pyramid, 32, 33, 120.
 Tobacco amblyopia, 141.
 Tone limen. See under *Eye and its reactions to light*.
 Trade revival, 57.
Trichromat, 140, 141.
 Trichromatic theory. See under *Colour analysis and synthesis*; also *Colour blindness* and *Colour vision*.
 Troland on colour vision, 120-2.
 Trotter, A. P., 46, 175.
 Tungsten lamps, 44, 47, 48.
 Turner, Joseph Mallord William, 65.
 Tyrian purple, 53.
- Uhler and Wood's Atlas, 71.
 Ultramarine pigment, 67, 73-6.
 Ultra-violet rays, 8, 9, 42, 46, 68-70.
- Vandyke brown, 73, 75.
 Van Eyck, 53.
- Varnish, 65, 67.
 Vecchio, Palma il, 55.
 Venetian painting, 55.
 Venetian red pigment, 72, 74, 76.
 Verdigris pigment, 73.
 Vermilion pigment, 66, 72, 75, 76, 180.
 Veronese green, 74.
 Viridian pigment, 72, 74.
 Visual fatigue. See under *Colour in human experience*; also *Colour vision*.
Visual Optics (L. Laurance), 77.
 Visual purple, 79, 123.
- Water-colour painting, 27, 53, 64, 66, 72, 74-6.
 See also *Pigments*.
 Watson, Professor, 93-5, 140, 149.
 Wave theory of light, 1-13.
 Weaving, 60.
 Weber's law, 89, 90.
 Welsbach lamp, 47.
 Westaway's *Scientific Method*, 117.
 Whatman paper, 64, 66.
 White lead pigment, 73, 75.
 Whitening pigment, 73.
 Wiener's researches in colour photography, 161, 162.
 Williams lantern, 145.
 Winch, J., 54.
 Winsor & Newton, 73.
 Wireless telegraphy, 9.
 Wood, R. W., 26, 70, 169-71.
 Wood engraving, 151, 152.
 Wratten filters, 72, 182.
- X-rays, 8, 9.
- Yellow lakes, 73.
 Yellow ochre, 72, 74, 76.
 Yellow spot. See *Macula lutea*.
 Young's discovery of colour blindness, 140.
- Zander's process, 158.
 Zenker's theory of light, 160.

PRINTED AND BOUND IN GREAT BRITAIN

By Blackie & Son, Limited, Glasgow







PLEASE DO NOT REMOVE
CARDS OR SLIPS FROM THIS POCKET

UNIVERSITY OF TORONTO LIBRARY

Physics	Martin, Louis Claude and
Optics	Gamble, William
M	Colour and methods of colour reproduction

Physical &
Applied Sci.

